博 士 論 文

MODELLING AND EVALUATION FOR POWER SUPPLY SYSTEM WITH CONSIDERATION OF SUPPLY AND DEMAND SIDES

供給と需要側を考慮した電源システムのモデリングと評価

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李　岩学

YANXUE LI

Modelling and Evaluation for Power Supply System with Consideration of Supply and Demand Sides

ABSTRACT

Renewable energy integration is expected to bring promising environmental benefit and energy self-sufficiency security at district level. Increasing share of variable renewable may pose challenges to grid integration, such as supply-demand balance and power quality maintenance. The shape and variability of electricity demand change significantly driven by economic growth and seasonal increasing indoor comfort requirement, demand side management is expected to provide potential grid flexibility. Meanwhile, improved power technologies are widely used in decentralized energy system, covering the electrical or heating loads. Modelling and optimization of sustainable power system and energy network are becoming complex engineering. Similar to integration and dispatch of renewable energy, decentralized energy systems in building sector need to be planned considering district supply-demand scenario. Potential benefits are expected to bring to both supply and demand sides under cooperative energy market scheme.

In this thesis, firstly, the research background and purpose of the thesis are provided. By reviewing previous researches, renewable integration impacts and assessment approaches are identified. Then a relatively simple feasibility study of virtual power plant in Chongqing Island is investigated based on cooperation of supply and demand side resources, results verified its effectiveness and states renovation in energy market. For further investigations, integration and dispatch of massive PV generation is analyzed in detail, focusing on impacts of grid flexibility and generation cost in Kyushu. Potential techno-economic performances of distributed energy resources with coordinate demand side management are evaluated in residential building sector, price-based demand response is examined based on the next generation social demonstration projects. In addition, possible market innovation and implication are introduced.

In chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY, presents the worldwide situations of renewable technology development, then states the opportunities and challenges for power supply system with increasing variable renewable integration, provides the importance of coordinate demand side management. Finally, illustrates the motivation and purpose of this research. In addition, the energy roadmap and relevant policies in Japan is described and related studies have been reviewed.

In chapter 2, RESEARCH MOTIVATION AND METHODOLOGY. Firstly, the

concept and approach for load leveling is introduced. Then previous research about impacts of renewable energy integration and role of storage system are investigated. Finally, the assessing approaches are illustrated, including residual load duration curve, screen curve method and evaluation for demand side management from bottom up approach.

In chapter 3, FEASIBILITY ANALYSIS OF VIRTUAL POWER PLANT. Feasibility of Virtual Power Plant (VPP) in Chongming Island is investigated, VPP is constructed based on resources from both supply and demand sides, strategies focus on expansion of renewable energy and upgrade of home appliances in demand side. Analysis results verify the effectiveness of VPP concept based on cooperation between supplier and customer. Achieved district annual power saving 273GWH/year, the energy market structure is changing due to the application of the VPP, balancing benefits of power utility and consumer.

In chapter 4, ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN PLANT SIDE. The techno-economic viability of high variable renewable integration, grid flexibility and storage is investigated in this section. Firstly, electricity load and PV production of Kyushu Island are described. The impacts of increasing PV integration is illustrated in load duration curve, PV curtailment has occurred when PV production to grid load ratio is over 10%. Storage dispatch is important for higher PV integration, PV-PHS dispatch scenarios are carried out based on simulation model with constraints, results indicate that pump hydro storage can play an effective role in promoting PV utilization via absorbing excess PV generation under grid flexibility limitation, PHS also effectively helps shave the peak load, enhancing grid flexibility. PHS effectively recovers the suppression and decreases the PV levelized cost of electricity especially under higher PV penetration. Meanwhile introduction of combined PV and storage system (PV-PHS) shifts the curve of power supply merit order to right, decreasing the overall power generating cost. Increasing RES integration shifts power supply merit order to right and decreased the output from medium base plants (LNG or coal), effects of peak reduction reduce the output from peak-meeting plants with higher generation cost. Simulated result shows PV-PHS can decrease the overall generation cost from 0.145$/kWh to 0.139$/kWh at 19% PV penetration level of public grid, pumping ability to peak load ratio is 0.15.

In chapter 5, PERFORMANCE ANALYSIS OF DISTRIBUTED ENERGY SYSTEMS. Firstly, introduces the motivation behind demand side management and illustrates the social demonstration projects in Kyushu. Then describes the demand side high efficient technology developments. To get a better understanding of behaviors of efficient power technologies based on their real applications in social demonstration projects. Then investigated the cost saving and environmental benefits of decentralized energy systems in residential sector under current energy market. Results indicate that combined thermal storage and heat pump could be scheduled to lift the early morning valley period effectively. V2H brings more flexible option to the grid, aggregated EVs lifts valley grid load and shaves the night peak period in absence of PV generation, potential cost saving and carbon emission reduction are achieved due to reduction of gasoline fuel consumption. Generating ability of PV system shows great variations over months, the application of battery storage in residential PV system is investigated in detail. Aggregated PV-battery system can be scheduled to increasing local self-consumption, meanwhile serve the grid-supporting peak shave. Relevant subsidies or further cost drop in battery is essential for the preference of grid-supporting PV-battery system in residential sector. Operation of cogeneration system (Fuel cell) highly depends on simultaneous thermal and power loads, power contribution shows limited contribution during summer or mid-season. The economic feasibility of CHP system is still highly dependent on access of direct subsidy due to high initial capital cost under current energy market. Scheduled distributed energy resources could shave the peak grid load to reduce the output from peak-meeting plant, further decreases the overall generation cost, providing potential benefits to both utility and consumer.

In chapter 6, MARKET INNOVATION AND SUGGESTIONS. Attitudes and human behavior need to be modified toward more efficient and conscious energy usage. The performance of dynamic price based demand response is investigated based on the social demonstration project experiment. The behaviors of change in daily electricity consumption curves can be obviously observed in types of consumer sectors under the designed CPP (critical peak pricing) event, their response effects are described and compared. From demand side management perspective, the integration of electrical technologies in demand side can provide flexibility to the public grid in a decentralized way. Reasonable subsidy or relevant incentive policy to grid-supporting power storage and residential CHP system is essential for their wider development considering their potential flexible resource and carbon emission reduction chances.

In chapter 7, CONCLUSION AND OUTLOOK. The conclusions of whole thesis is deduced and the future work about optimization of power system has been discussed.

李 岩学 博士論文の構成

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Chapter 1

BACKGROUND AND PURPOSE

CHAPTER ONE: BACKGROUND AND PURPOSE

1.1 Introduction

Nowadays driven by economic growth and life quality improvement, the world is facing great challenges of the energy shortage and increasing carbon dioxide emissions problem. Energy Information Administration released International Energy Outlook 2013 (IEO2013) projects, points that world energy consumption will grow by 56% between 2010 and 2040, estimated carbon dioxide emission will rise to 45 billion metric tons in 2040, a 46% increase from 2010 level. Long-term continued reliance on fossil fuel consumption accounts for most of the emission increases. Global CO_2 emission has increased by 52% from 1990 to 2012, the increase in power sector reached 91% during the period. Renewable energy is highlighted as a solution for those challenges, many long-term integrated assessment scenarios and bottom up source assessment studies show that renewable energy exploitation have the potential to play a central role in achieving ambitious climate mitigation target. Meanwhile, in demand side the energy intensity of building sector is increasing with the higher requirement of indoor quality, building sector contributes significantly to the total energy consumption and accounts up to 45% of the primary energy consumption in some countries. Taking into account the high energy intensity of the residential sector, a possible vast demand side resource potential could be unveiled.

With continuing cost drop in renewable power technologies such as PV, wind and battery storage, there is a increasing trend of renewable integration in public grid. The increasing amount of renewable energy also presents a further threat to security of electricity power supply. It may lead renewable generation curtailment under high renewable penetration level with consideration of grid flexible limitation. Utility has to prepare significant amount of controllable power plant capacity or dispatch storage systems to absorb the fluctuations and balance real time demand load. Concerning this issue, research about resilient operation of power grid and energy market effects of increasing renewable energy are getting more attentions than before. Meanwhile, demand side management (DSM) as virtual power resource is expected to play an increasing role in increasing the grid flexibility for the incorporation of higher shares of variable renewable generations.

Advancement and development in smart meter, internet and communication technologies enable the interconnection between district energy utility and customer, provide utilities real-time scheduling strategy for power supply system, and chances for customers to participate more in local grid management via coordinate control of home appliances or local power resources. Contexts of DSM in community or micro grid generally focus on uptake of energy efficient appliances, coordinate control of local power technologies and induced load pattern shift. Driven by cost saving potential and relevant incentive policies, there are growing interest in uptake of energy conservation technologies and real time power consumption control in demand side, generally called demand response strategy, and district utilities pay more attention to potential benefits of demand response applications, such as generation cost saving, load leveling and carbon emission reduction.

For optimization of future low carbon and efficient power supply system, this research focuses on three major aspects: (i) Expansion assessment of variable renewable energy resources, optimal integration and dispatch considering grid flexibility, concentrating on PV integration and dispatch considering its great daily variations. (ii) Application evaluation of high efficient technologies in next generation social demonstration projects, assessment of demand response effect from a bottom up approach. (iii) Energy market implication and suggestion.

Table 1-1 Key effective technologies in reducing CO_2 emissions

Supply side	Demand side
CCS fossil-fuel power generation	Energy efficiency in buildings and appliances
Nuclear power plants	Heat pumps
Onshore and offshore wind	Solar space and water heating
Biomass integrated-gasification combined-	Energy efficiency in transport
Photovoltaic systems	Electric and plug-in vehicles
Concentrating solar power	H_2 fuel cell vehicles
Coal: integrated-gasification combined-cycle	CCS in industry, H_2 and fuel transformation
Coal: Ultra-supercritical	Industrial motor system
Second-generation biofuels	

Note: CCS is Carbon Capture and Storage

Low carbon transformation in power sector and demand side management are expected to play increasing roles in developing sustainable energy system and reducing global greenhouse gas emission. International Energy Agency (IEA) has selected 17 key technologies in reducing CO_2 emission, located in supply and demand sides as illustrated in Table 1-1. Fig.1-1 & 1-2 present current generation cost of main power technology and emission factor by source in Japan. Meanwhile, there is expected cost drop trend in renewable technologies (METI 2015), for example, overall generation cost of PV is expected to experience further decrease from 0.22$/kWh in 2014 to 0.12$/kWh in 2030. Renewable energy technologies are expected to experience a promising market over coming decades.

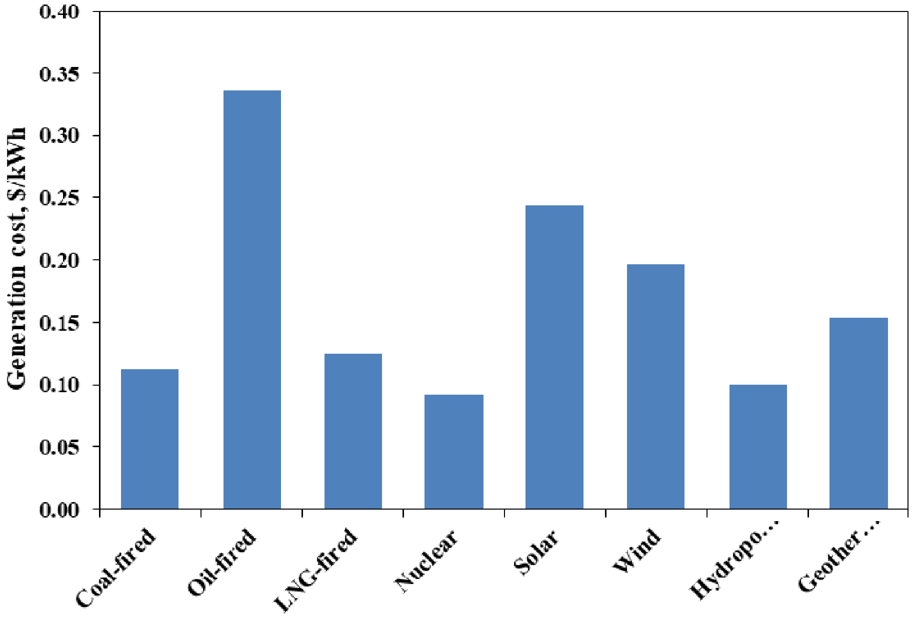


Fig.1-1. Electricity generation cost by source, reference: Power Generation Cost Verification Working Group 2015

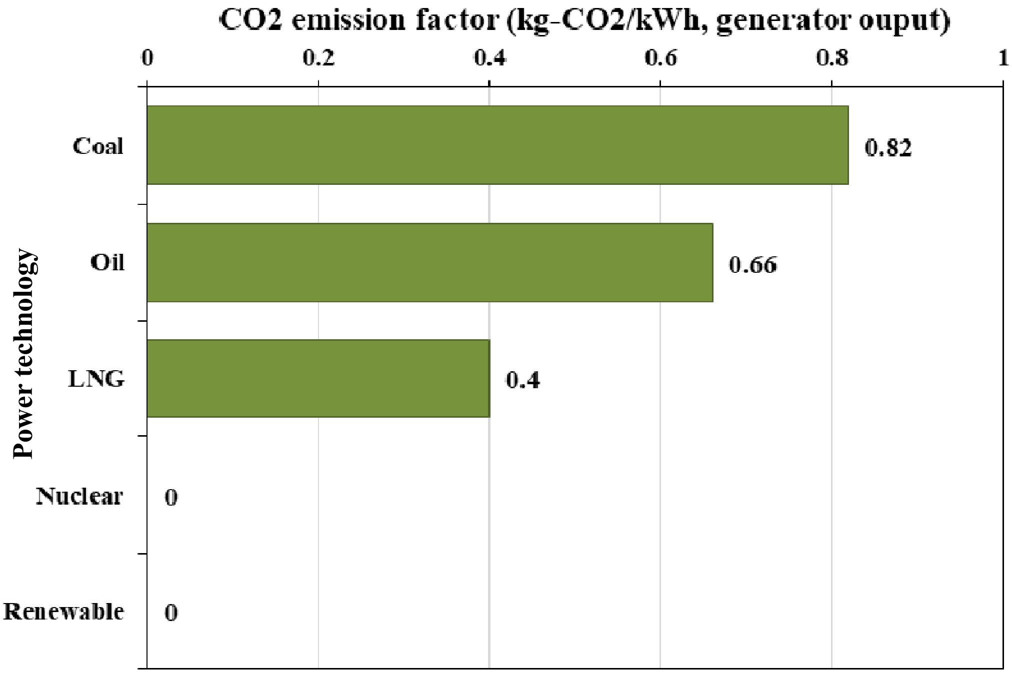


Fig.1-2. Electricity generation carbon emission factor by source, reference: Power Generation Cost Verification Working Group 2015

1.2 Research Background

1.2.1 Worldwide RES integration and development

Government incentive policies, continuous cost drop in renewable production, improvement in renewable output prediction and coordinate output control jointly accelerated the development of renewable energy resources. According to renewable capacity highlight of international renewable energy agency (IRENA, 2018), global cumulative renewable generation capacity amounted to 2197 GW by the end of 2017, experienced 8.3% (167 GW) growth during 2017, new installations of solar and wind energy accounted mostly of all new capacity installed, increase 94 GW and 47 GW in 2017 respectively. As illustrated in Fig.1-3, growth of wind and PV has been an exponential curve over recent years. According to the IEA hi-renewable scenario, 16% of global electricity will be supplied by solar PV power by 2050. Meanwhile, renewable energy technologies have become dramatically cheaper to produce and store as shown in Fig.1-4, which further accelerates the worldwide installation of the PV and wind recent years.

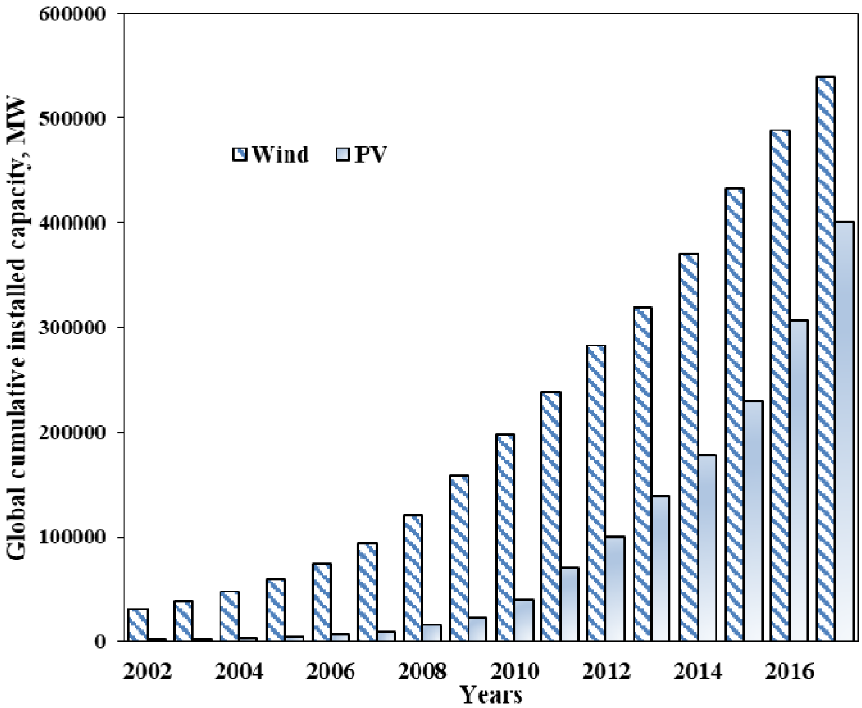


Fig.1-3. Global cumulative installed wind and PV capacity, reference: Statista IRENA, 2018.

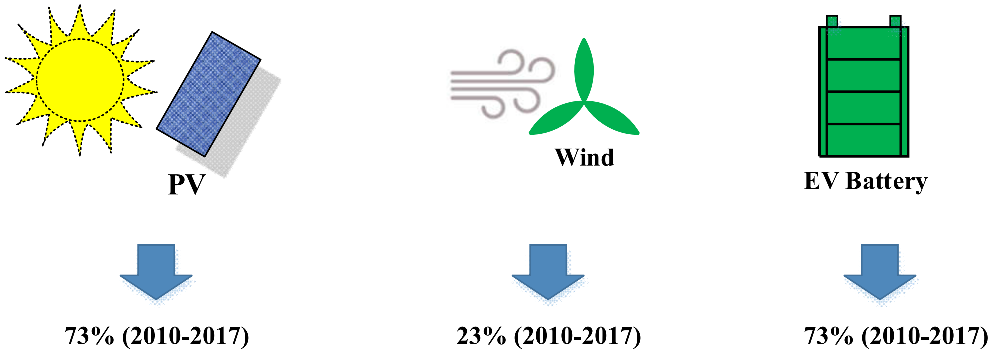


Fig.1-4. Cost drop of renewable technologies from 2010 to 2016, reference: IRENA, 2018

Renewable energies are becoming an important part of district or national scale power grid, particularly in regions of developed countries like Germany, Japan and United States. Germany has been called as 'the world first major renewable energy economy', the share of renewable energy resource in electricity consumption has increased from 9.3% in 2004 to 25.4% in 2015 [1], the proportion of power produced by renewable energy reached 35% in first half of 2017, it has been getting up to 85% of its electricity from renewable sources on certain sunny, windy days. Germany has declared goal to cut carbon emissions by 80% by 2050 compared to 1990 levels, which requires near total decarburization of the electricity sector. The Germany aims to accomplish at least 50% of electricity from renewable energy by 2030, renewable energy sources act has stimulated tremendous investments in renewable energy generation capacities since 2000, more than 30% of Germany's electricity was renewable energy by 2016 [2]. UK sets a similarly 45-55% share of renewable energy to meet national carbon budget by 2030, combined wind and solar capacity grew from 5.46GW in 2010 to 27.25GW at the end of 2016. Germany government is aiming to phase out its nuclear power plant by 2022 [3]. Solar and wind energy markets in the U.S. have exploded as compared to other renewable energy resources, photovoltaic (PV) installation reached 6112 MW in 2014, cumulative wind capacity reached nearly 74000 W by the end of 2015. As nation's leading renewable-energy proponent, California has set ambitious requirements to reduce state's greenhouse gas emissions 40% below 1990 levels by 2030, annual solar and wind penetration levels reached 10.8% and 9.3% in 2017, respectively. And local utility announced to raise renewable energy resources to 33% of electricity retail sales by 2020 and 50% by 2030 [4]. Japan government set a renewable energy mix target for power sector, 22-24% penetration level by 2030, increasing the national energy self-sufficiency to be higher than the scenario before Great East Japan Earthquake. Grid connected renewable resources experienced a rapid expansion since the lunched feed-in tariff scheme and retail liberalization. For example, the PV penetration level in Kyuden Company has reached 10% during 2017 with cumulative 7500 MW integrated PV capacity.

For many regions in developing Country, such as China and India, the energy consumption are supposed to be higher in the future due to the rapid development of social economy. Therefore, a sustainable society needs to develop its own power supply-demand system in an economical, environment friendly and secure way. The integration of distributed renewable energy resources has been introduced as an effective way to address the power shortage and minimize negative environmental impacts. Historically the promotion of renewable energy technologies has involved international donors or governments subsidizing the initial capital investment. Ref [5] presented the evaluation of the renewable energy premium tariff (RPT) scheme, a locally adapted variation of the feed-in tariff tailored for decentralized grids of developing countries, RPT provide chances for policy maker to reduce the environmental cost and enhancing local energy self-sufficiency. Empirical results indicate that economic growth generally leads the power consumption and emissions, Ref [6] explores the effects of share and size of renewable consumption on carbon emissions, results indicate that increasing share of renewable energy contributes to the carbon reduction, lessen the dependency on fossil fuels, the promotion of commercial service trade is share of renewable energy consumption is important for low carbon economic growth in developing countries. Coal fired power plants contribute to 69.5% of power generations, account for 80% of total electricity power generated in India. Rapid economic growth leads the increasing power consumption, power deficit of 6103 MW was experienced during the financial year 2014-2015 [7]. Estimated peak electric demand may reach 298 GW in 2021, 37% increase compared with 2016 level. With a vision of sustainable development, the government is promoting cleaner sources of energy and has set a target of 175 GW renewable capacity, including 100 GW solar and 60 GW wind by the year 2022 [8], the installed PV and wind capacities are expect to experience an exponent increase over coming decades [9]. China increasing serious energy and environmental issues are loosely related to China’s coal-dominated energy structure [10]. Triggered by national industrialization and urbanization, power consumption experienced rapid development over past decades, energy demand escalated at the rate of 40% from 2003 through 2010, energy shortage and emission increase become major focus of government policy initiatives [11]. In 2017, total installed power capacity increased by 7.6% year on year to 1.8 TW in China, non-fossil capacity accounted for 38.7% at 690 GW, edging up 2.1 percentage points from the year prior. Thermal power occupied an absolute dominant position (78.6%) in China. In order to achieve the goal of improving the level of economic development while reducing energy consumption, China government pushed relevant incentive policies to accelerate the renewable energy development. Total installed renewable energy capacity increases from 41.8GW in 2010 to 148.6GW in 2016 [12]. Cumulative capacity solar PV has amounted to 77.42GW by the end of 2016, ranking the first worldwide for two consecutive years. Meanwhile, China has set ambitious goals for wind power and solar power, reach 2400 GW and 2700 GW respectively by 2050 [13].

1.2.2 Development of electricity storage

Due to the variable and intermittent nature of the output of renewable energy, increasing high renewable energy penetration level may cause grid network stability problem. To guarantee the stability of the power supply and smooth the net load variation in grid, electricity storage systems are needed. As variable renewable generation is expected to reach large penetration levels in the decades, energy storage will play crucial role in maintaining grid reliability and security standards, particularly in isolated grids. Energy storage is a vary varied subject area with multiple technologies and multiple applications: from small-scale such as battery storage for distributed PV installations with a few kW to large scale (pumped hydro of several hundred MW). From short duration for grid frequency response to seasonal dispatch such as hydro pump storage system, power to gas. Fig.1-5 illustrates the categorization of storage, CAES is compressed air energy storage, LAES presents liquid energy storage. The global installed storage capacity reaches 171.05GW, consisting of 1267 projects, Fig.1-6 illustrates the ratio of rated power storage capacity in the world.

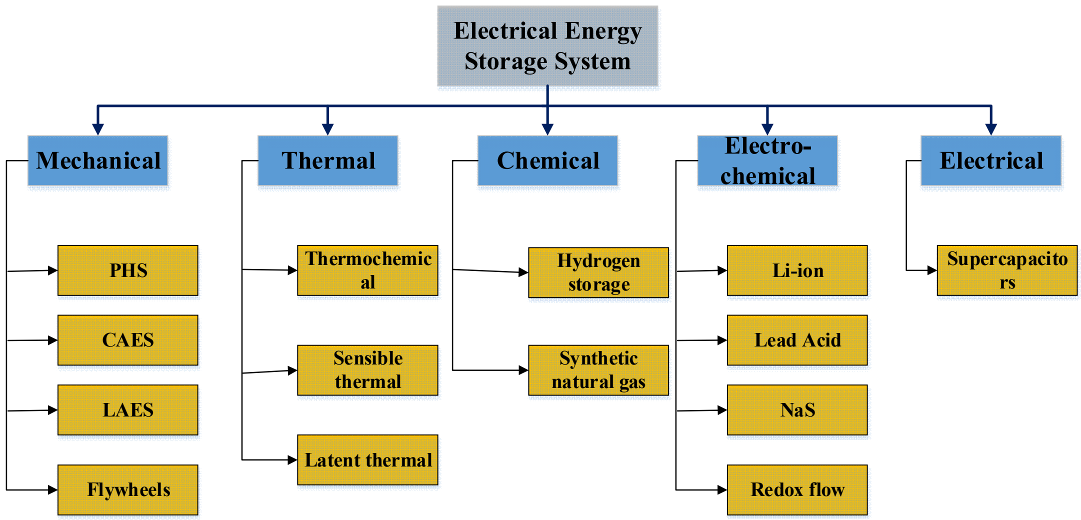


Fig.1-5. Scientific categorization of storage, reference: world energy council

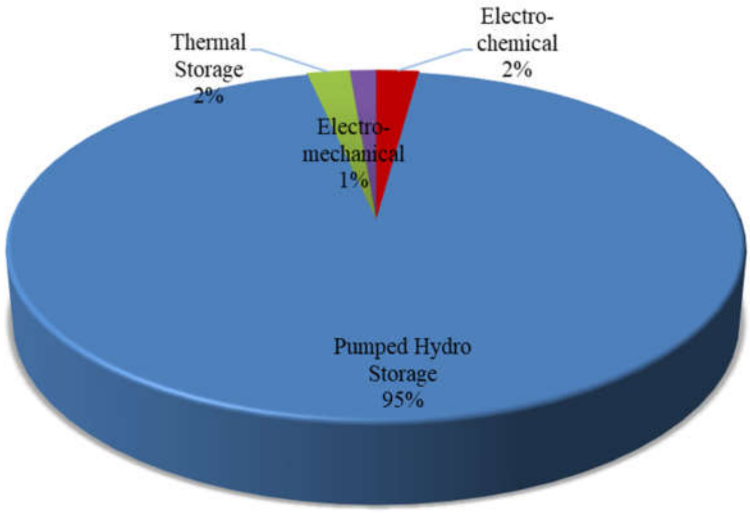


Fig.1-6. Percentages of rated power storage capacity in the world, reference: DOE Global Energy Storage Database, 2018

Pumped hydro energy storage is the dominant form of world-wide energy storage because it is an established technology, is cheap and provides a broad range of support services for the electrical grid, pumped hydro storage accounts for well over 95% of global installed energy storage capacity. Pumped storage hydropower is a modified use of conventional hydropower technology to store and manage energy or electricity. Pumped storage system stores electricity by moving water between an upper and lower reservoir, the stored water is released back through the turbine and converted back electricity like convention hydropower station during the peak period. Various benefits could be brought to the grid, such as provides frequency support to reduce the rate of change of frequency during grid disturbances, rapid power response to changes in demand with changes from 0-100% power possible in 1 minute, such repose time is very suitable to the variations in power from renewable sources such as wind or photovoltaics, or rapid changes in demand. Application roles of storage play in the public grid can be summarized as following:

- Leveling load, provide backup electricity, storing during off-peak, and selling it during peak
- Frequency regulation, keep balance between supply and demand
- Diversifying generation portfolios, promoting renewable energy penetration level
- Peak shaving, reduce the total generation capacity required
- Enhancing the safety and reliability of power supply
- Lowering operational cost for utility and saving electricity expenses for end customer

Rapid growth of electric vehicles and need to integrate distributed renewable technologies, are driving huge investments in the development of battery technologies. For example there are around 25000 domestic installations in Germany alone in conjunction with PV installations, with total capacity of 160 MWh. Millions of water heater have been operated in France for decades, they provide a massive benefit in reducing peak periods to valley demand periods. In recent years, this is due to the significant performance improvements and cost reductions, lithium-ion technology has become more popular and it is expected to become the dominant battery storage technology in decentralized form. Flow battery if developed further, it is expected to be a game changer in utility-scale energy storage. Main attributes of representative batteries are summarized in Table 1-2.

Table 1-2 Main attributes of representative batteries

Type	Lead-	NiMH	Li-ion	NaS	VRB
Energy density (Wh/kg)	25-50	60-120	75-200	150-240	10-
Power density (W/kg)	75-300	250-	500-2000	150-230	80-150
Cycle life (100% depth of	200-1000	180-	1000-	2500-	>12000
Capital cost ($/kWh)	100-300	900-	300-2500	300-500	150-1000
Round-trip efficiency (%)	75-85	~65	85-97	75-90	75-90
Self-discharge	Low	High	Medium	--	Negligible

Reference: Hu, X., Zou, C., Zhang, C., & Li, Y. (2017). Technological developments in batteries: a survey of principal roles, types, and management needs.

1.2.3 High efficient technologies development

Globally, the world primary energy consumption proportions for residential, commercial, industrial and transportation were 22%, 19%, 31% and 28% respectively. The building energy consumption has accounted for a large proportion, 41% in US, 40% in Europe, 25% in Japan, 28% in China [14, 15]. Buildings accounted for 32% of total global final energy consumption (24% for residential and 8% for commercial), appliances presents 9% of this energy consumption in residential buildings as illustrated in Fig.1-7, which comprised 180GWh in 2010. In the next decades, the energy consumption of residential sector will rise due to the proliferation of equipment types used and their increased ownership and use. The 5th Assessment Report of the Intergovernmental Panel on Climate Change stated that energy efficient appliances, lighting, information communication, and media technologies are expected to reduce the substantial increase in electricity use expected. Taking into account the high energy intensity of the building sector, varying 20-40% of total energy consumption in different countries. Energy saving efforts concentrates on enhancing efficiency of electric appliances and smart energy management via automatic control. Utilities spend millions of dollars annually to improve appliance energy efficiency. For example, in California alone in 2013, utilities spent $80 M on appliance and plug load efficiency programs, the highest expenditure among all utility energy efficiency programs.

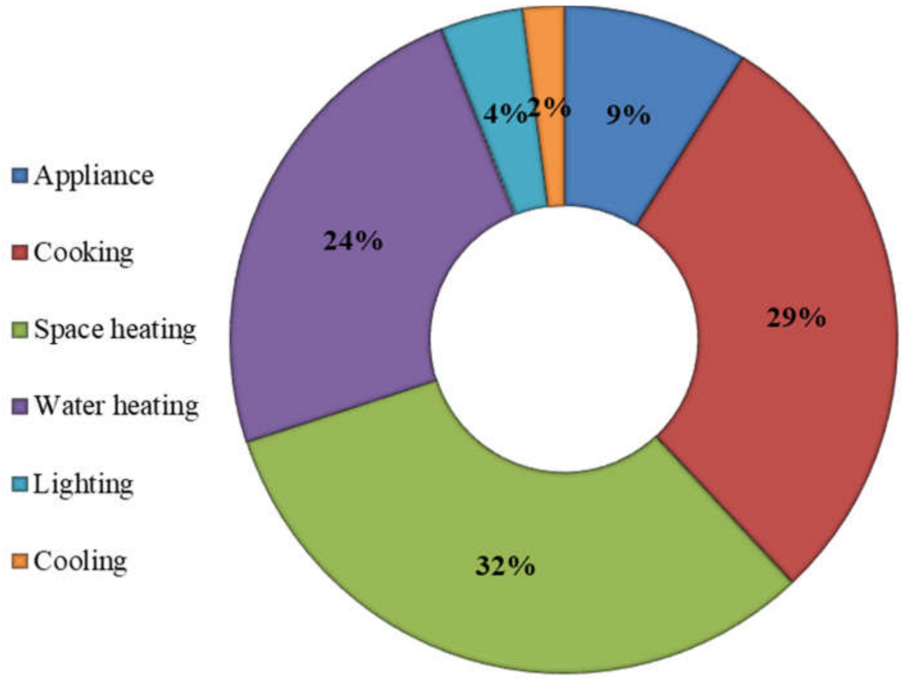


Fig.1-7. World residential building final energy consumption by end-use, reference: 2010, IEA

The aggregated uptakes of high energy efficiency appliances and on-site generators are expected to participate more in compensating increase in load and developing sustainable energy system.

Current energy efficiency efforts and activities in building sector have been focused towards improving energy saving in appliances [16, 17], coordinated managements of grid-connected on-site generators [18-20], and demand response implementation driven by potential cost benefits brought to both plant and customer sides [21-23]. China's status as the world's largest home appliance market and its huge demand for electricity are key factors driving the introduction of a new program to improve energy efficiency across high-energy-consuming industries, including the home appliances sector, China has implemented a series of minimum energy performance standards (MEPS) for over 30 appliances, voluntary energy efficiency label for 40 products, and a mandatory energy information label that covers 19 products to date, standards in place in China for residential and commercial appliances are expected to save cumulative 6947 TWh by 2030, account 14% of cumulative electricity consumption of buildings[24]. Energy consumption level have a rapidly increased since the layer half of 1980s in residential and commercial sectors in Japan. Highly energy efficient home electric appliances and office devices including air conditioner, heat pump, refrigerators and other devices have been developed and supplied to domestic market driven by the national 'Top Runner Program', the growth of energy consumption level in those sectors has been restrained for about recent 15 years. Fig.1-8 presents parts of achieved energy efficiency through Top Runner Program in Japan. It should also be noted that going any deeper with energy conservation is not easy, because uncompromising enhancement of energy conservation will require understanding and cooperation from the public as well as specific measures to ensure implementation.

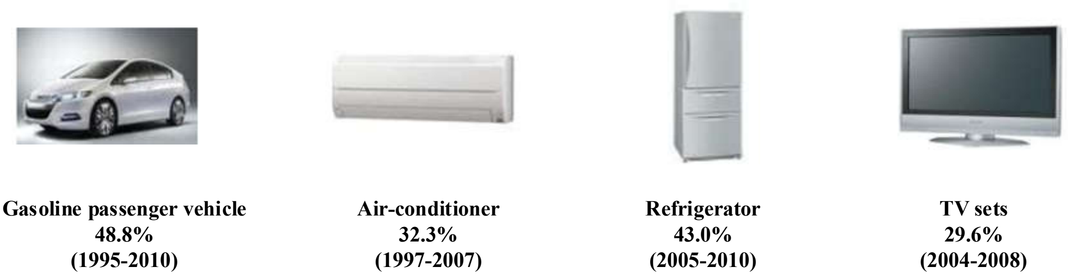


Fig.1-8. Achievements of the Top Runner Program in Japan, reference: 2016 IEEJ

According to the national energy efficiency trends and policies, Germany improved 15% of the overall energy efficiency in 2013 compared with the base year 2000, the specific electricity consumption of major household appliances in Germany decreased via improving energy efficiency [25]. Japan government pushed various energy saving strategies in demand side during the tight power supply-demand balancing period after Big East Earthquake occurred. Flexible energy technologies, such as fuel cell and heat pump systems, widely installed in demand side, heat pump water heater system, named as Eco-cute can effectively to shift peak heat demand to valley period, meanwhile, high energy efficiency performance helps reduce the emissions compared with conventional energy supply system.

1.2.4 Smart energy management strategies

Major changes in the energy sector in recent years mean that the need for smart, flexible energy is increasing, and that energy production and storage facilities will have to become more coordinated. In the future Smart Grid, every facility and device will have its own IP address so that it can be monitored and controlled via the Internet. It is expected that markets related to “smart technology” will expand as it contributes to energy conservation and improves the convenience of everyday life. The Internet of Things (IoT) is an emerging technology in which smart devices are interconnected and communicate via the Internet. Devices could be incorporated into the IoT, from air conditioners and TVs to cars and solar panels. It can be used on different platforms to support a diversity of devices and the development of IoT applications. Technology optimists claim that IoT technology will be the vital missing link enabling us to meet the major challenges associated with climate change, energy efficiency. The new technology will also create new products, new services, and new applications. Small energy producers, urban districts with energy-plus houses that produce more electricity than they consume, and motorists with electric cars that are part of a cooperative scheme can feed energy to the grid and act as energy companies. Smart management in demand side is not only embodied in integration of devices, but also the information exchange between the utility and customers. Smart meter and wireless communication framework enable the real time control of power technology consumptions and provides market cooperation potential between supply and demand sides based on demand side response strategies [26, 27]. As illustrated in Fig.1-9, the installation of HEMS makes it possible to “view” the consumption of electricity and gas as visible information and control HEMS-compatible home appliances automatically. Because it avoids wasting energy and reduces energy costs, HEMS is an essential part of Smart House technology. Smart meters, air conditioners, water heaters, lighting devices and other devices are connected to HEMS. Home energy management system (HEMS) enables smart houses, generally equipped with on-site generators, to gather the real time energy production, consumption and pricing, that shift their energy consumption based on signal from among communication network [28]. HEMS also enable customer to participate in the grid management from aggregated form, applied HEMS algorithm receives the price information from the utility company in advance and control starts and schedule the power consumption of home appliances. Meanwhile, bring cost saving to customers via load shifting [29].

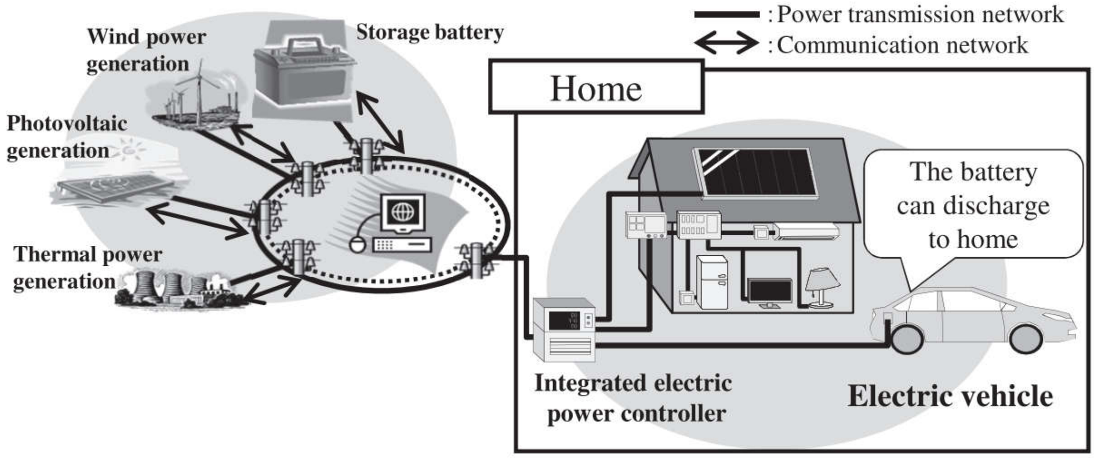


Fig.1-9. Structure of home energy management system (HEMS), reference: [30]

This Navigant Research report analyzes the shift in the smart appliances market as a subset of the smart home IoT trend and what this shift means for the many stakeholders, which include manufacturers, retailers, utilities, home builders, regulators, and insurers. Smart management of appliances in demand side are expected to become a much more robust market segment that benefits both buyers and sellers. High prices, other factors complicate growth prospects for smart appliances, utilities may use influence to spur smart appliance adoption. CEMS can provide opportunities to utilize the IT technologies and enable various support to service both power suppliers and demand users.

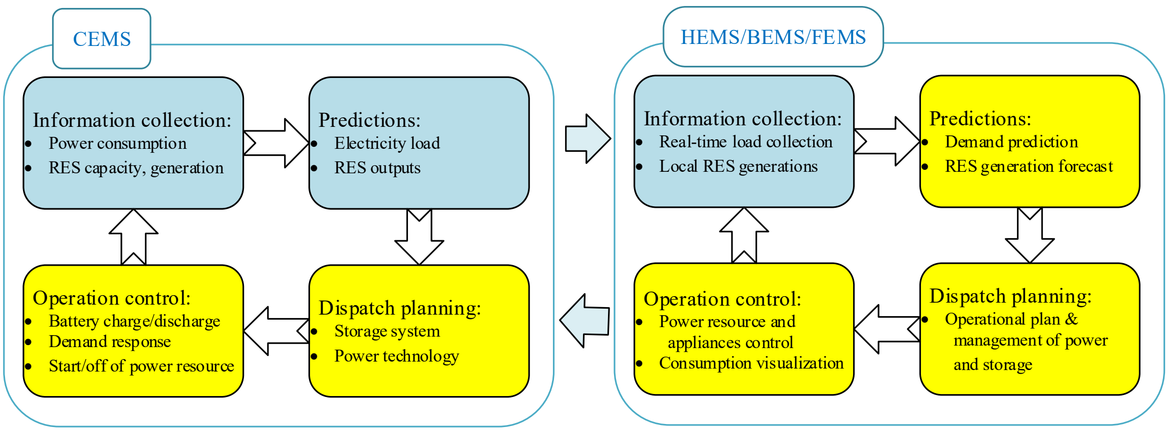


Fig.1-10. Communication network and context of CEMS

Fig.1-10 shows the network and operational processes of CEMS. CEMS can receive power consumption and send notification of real-time power price, and exchange power consumption information with types of consumers through bi-directional communication network. Solid line presents the electrical power flow, dot line presents the information flow consisting of electricity price signal and power consumption information. Customers who installed BEMS and HEMS can directly control the load of electric appliances within the buildings corresponding to the information of the real-time dynamic electricity price. The smart meter provides CEMS's request for demand response, and indoor indicator displays the dynamic price information [21]. Smart meter facility is widely installed in Japan electricity utilities. The utilities have agreed to utilize communication infrastructure that support hourly meter reading for low-voltage users and half hourly meter reading for high voltage users. For example, Kyushu has already equipped all commercial and industrial customer with smart meter by 2013, and plans to reach half of its residential customer by the end of 2019, and 100% by the end of 2023. The motivation behind such high sampling rates is to support new demand-side management initiatives, including customer feedback as well as provide better strategy for supply-demand balancing.

1.3 Overview of recent energy policy and development in Japan

Currently the power supply framework in Japan is mainly a mix of coal, natural gas, oil, nuclear, geothermal, biomass and renewable energy resources (RES). As shown in Fig.1-11, nine regional privately owned and managed General Electricity Utilities— Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku and Kyushu Electric Power Companies — were established in 1951 and assumed the responsibility of supplying electricity to each region. The frequency of grid power differs between eastern and western Japan, namely 50 Hz and 60 Hz respectively. Thermal power plants in Japan has already possessed a higher power generation efficiency compared with many countries over the world. However, Japan is still weak in RES exploitation compared with other environmental pioneers, such as Germany and Norway.

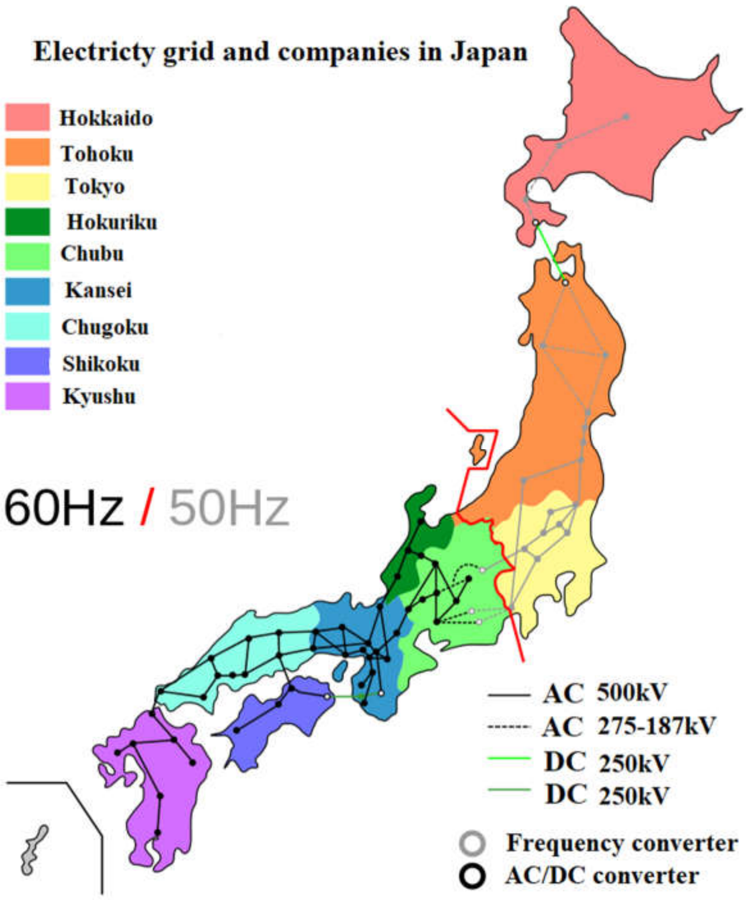


Fig.1-11. Nine electric power companies by main service area in Japan

After Fukushima crisis, thermal generators accelerate their generation to replace the loss of nuclear plants. In order to tackle tight grid demand-supply balance pressure during peak periods, enormous political and technical efforts were taken to replace the loss of the nuclear energy after the Great East Japan Earthquake. Maximizing the renewable source integrations in its power supply fraction has become a key political agenda, PV generation is playing an important role in enhancing national energy self-sufficiency after the feed-in tariff launched from 2012 in Japan. A number of studies assessed long-term energy mix and essential management on future sustainable power supply system from policy and technical perspectives, focusing on maximizing renewable penetration level, grid-supporting integration or dispatch and CO_2 intensity reduction of electricity sector. Fig.1-12 illustrates the carbon emission reduction target for each sector, residential sector faces a heavy emission reduction mission.

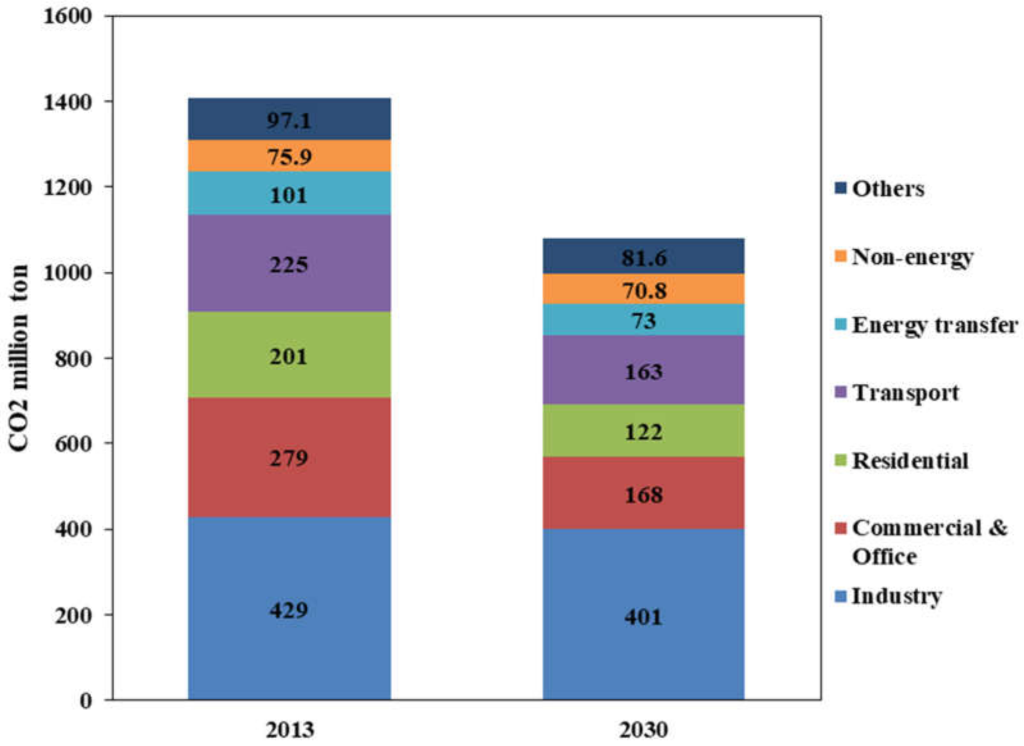


Fig.1-12. Emission reduction target for each sector in Japan

Following the ambitious carbon reduction target, METI established the long term energy/power supply and demand strategic plan. Outlook is a forecast and also a vision of a desired future energy supply-demand structure to be realized. Fig.1-13 describes the energy supply-demand outlook in FY2030, while expecting an increase in energy demand due to economic growth (1.7% per year), technologically feasible, realistic energy efficiency and conservation measures in the industrial sector, commercial sector, residential sector and transportation are accumulated to achieve approximate 50.3 billion liter (crude oil equivalent), resulting in final energy consumption of 326 billion liters in FY2030. The improvements will brings the national self-sufficiency ratio to approximate 24.3%.

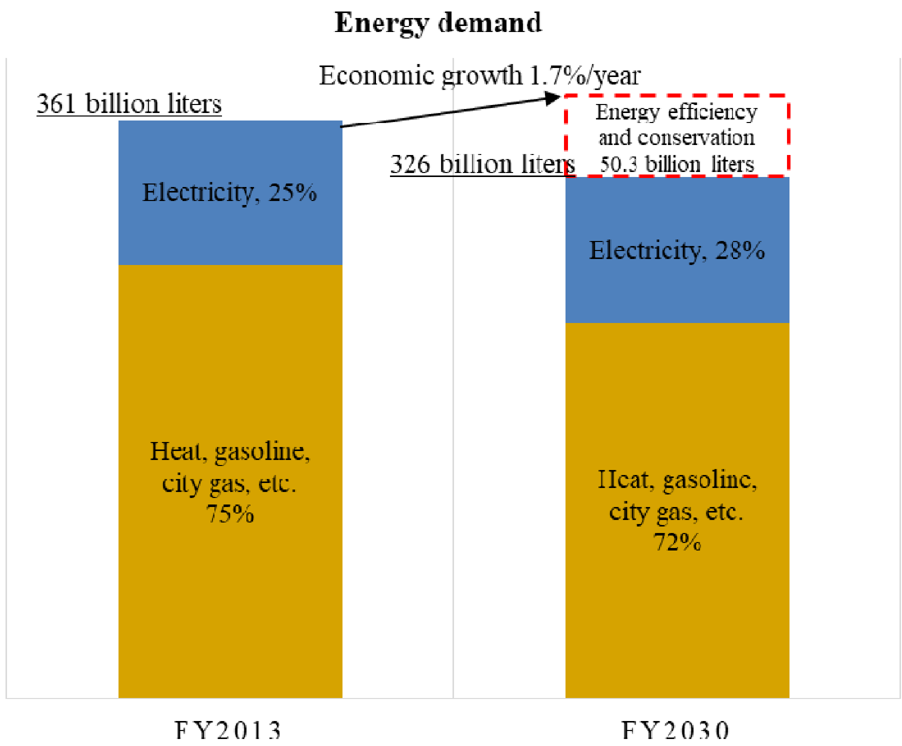


Fig.1-13. Outlook for emergency consumption in FY2030, Reference: material for 10th meeting of subcommittee on Long-term Energy Supply-Demand Outlook.

Fig.1-14 presents the outlook for power supply in FY2030, specifically while estimating an increase in electric power demand due to economic growth and higher electrification rate, thorough energy efficiency and conservation will be promoted to suppress power demand in FY2030 to nearly same level in FY2013. Fig.1-15 illustrates the detail structure of power supply, the improvements in energy conservation and expansion of renewable energy can joint increase around 40% the power self-sufficiency, reducing the dependence on nuclear & thermal power.

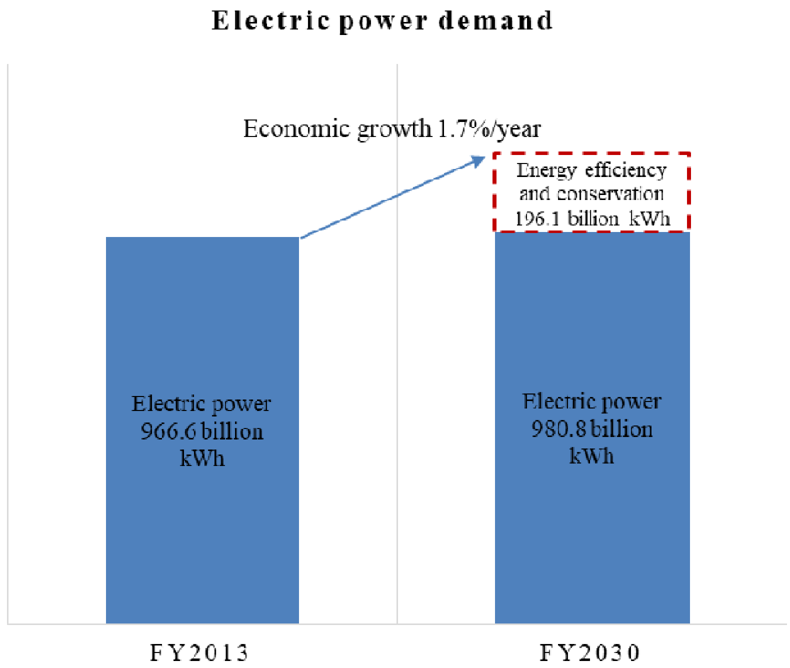


Fig.1-14. Outlook for Japan electricity demand in FY2030, reference: Reference material for 10th meeting of subcommittee on Long-term Energy Supply-Demand Outlook.

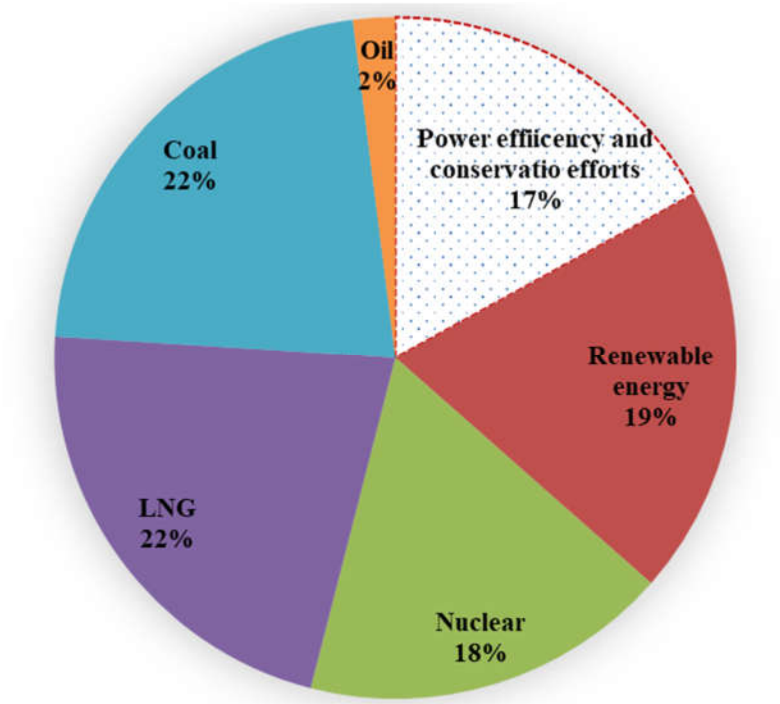
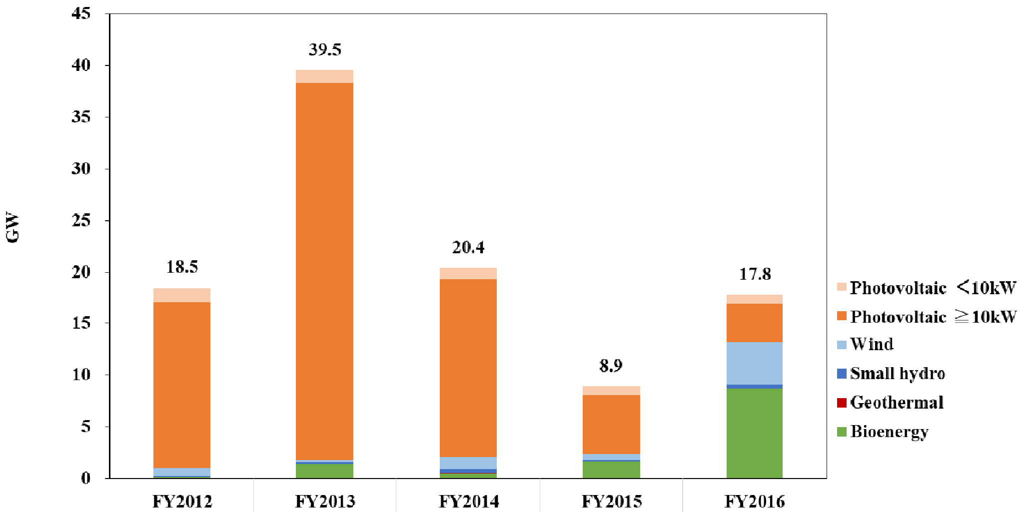


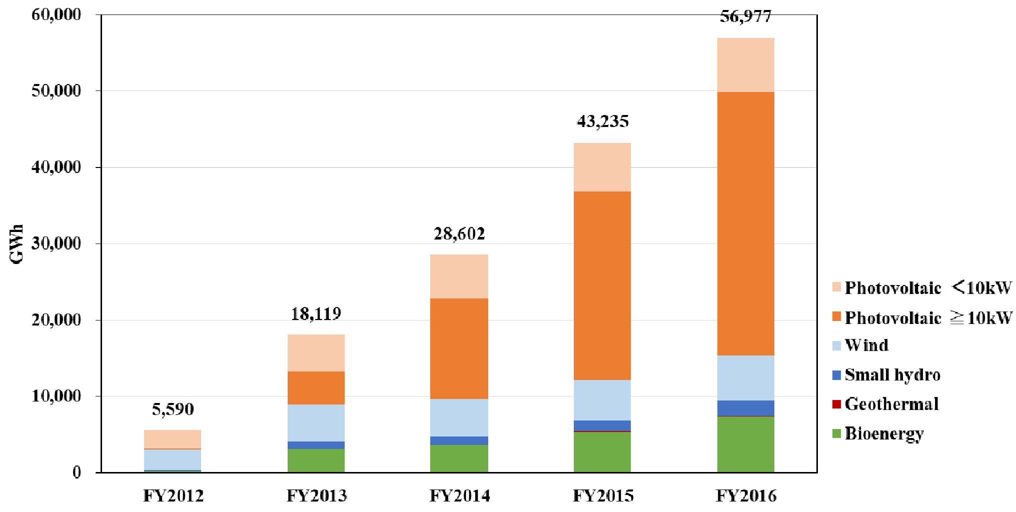
Fig.1-15. Outlook for Japan electricity component ratio structure in FY2030, reference: Reference material for 10th meeting of subcommittee on Long-term Energy Supply-Demand Outlook.

Analysis results of Ref [31] indicated that Japanese feed-in tariff rate generated a good profit for the PV system adopter, provided an acceptable payback period. Ref [32] analyzed integration of distributed PV in low voltage power grid systems, stated the importance of upgrade of power grid and subsidies to private sector for PV system effective diffusion. Ref [33] investigated the factors that affecting PV system adoption and purchasing behaviors in Japan, availability of feed in tariffs was highly correlated with consumer purchasing motivation. Ref [34] examined the efficiency of combined use of feed-in tariff and capacity subsidies to encourage household to adopt PV system, meanwhile change the feed-in tariff mechanism for parts of PV generation to maximize social welfare. Ref [35] examined an alternative option of creating power demand close to renewable sources in Japan rural area, instead of grid augmentation, renewable generation provides a significant merit for a sustainable future. Rise share of variable renewable resource will reduce the output from conventional power plants, and pose challenges to grid, such as flexibility variability maintenance, increased storage and reserve requirements. Ref [36] analyzed Japan's long-term deployment scenario of variable renewables with flexible power resources by developing a dynamic high time resolution optimal power supply mix model. Results show that high PV shares will decrease the capacity factor of LNG combined cycle plants or even lead VRE variable output suppression. Ref [37] pointed that lower rechargeable battery cost can decrease the PV output suppression rate after large-scale PV energy integrated into the grid. Ref [38] pointed that Japan could meet and exceed the ambitious carbon intensity reduction target by maximizing the regional renewable potentials, suggested political support and operate priority dispatch order on renewables over nuclear power plant. Renewables can maximize generation by promoting flexible grid operation and strengthening transmission capacity, pumped storage hydropower and demand response strategies will play an important role in stabilizing the power supply grid. Ref [39] estimated energy storage requirement of future mostly solar and wind (2:1 mixture) energy supply system of Japan, the system provides a good chance to meet around 40% of electricity demand between 11:00 and 18:00, it needs large capacity of pump storage to balance the demand during summer period. Ref [40] analyzed the national post-Fukushima power generation mix plan that puts a high priority on expanding renewable energy, simulated results show that massive VRE will decrease capacity factor of thermal power plant and affect its profitability, stressed the necessity for capacity expansion of power transmission lines and control on VRE variability. Ref [41] assessed the feasibility of a 100% renewable energy electricity in Japan by the year 2030, such system would use pump hydro storage and electric batteries to balance the daily fluctuations in supply and demand, grid system has to face summer peak demand challenge and the high initial balancing investment may impose an economic limitation. Ref [42] focused on the balance and match of future electricity supply-demand in Japan, increasing penetration of VRE can reduce the dependence on nuclear power and thermal power, it needs flexible power sources such as LNG, pump hydro-electricity to absorb fluctuations. Fig.1-16 & Fig.1-17 present registered renewable energy capacity and generation under feed-in tariff in Japan since 2011.



	FY2012	FY2013	FY2014	FY2015	FY2016
Photovoltaic ＜10kW	1.4	1.3	1.1	0.9	0.9
Photovoltaic ≧10kW	16.0	36.4	17.2	5.7	3.8
Wind	0.8	0.2	1.3	0.5	4.1
Small hydro	0.1	0.2	0.4	0.1	0.3
Geothermal	0.0	0.0	0.1	0.0	0.0
Bioenergy	0.2	1.4	0.5	1.7	8.7
Total	18.5	39.5	20.4	8.9	17.8

Fig.1-16. Registered renewable energy capacity under FiT in Japan, reference: REI, ANRE/METI Renewable Power Plant Certification Status



	FY2012	FY2013	FY2014	FY2015	FY2016
Photovoltaic <10kW	2,321	4,857	5,780	6,486	7,117
Photovoltaic ≧10kW	190	4,255	13,177	24,591	34,550
Wind	2,742	4,896	4,921	5,233	5,862
Small hydro	120	936	1,073	1,476	2,008
Geothermal	1	6	6	59	76
Bioenergy	217	3,169	3,644	5,390	7,365
Total	5,590	18,119	28,602	43,235	56,977

Fig.1-17. Registered renewable energy generation under FiT in Japan, reference: REI, ANRE/METI Renewable Power Plant Certification Status

Recent energy policies place extensive focus and efforts on the power security concern, such as large integration of distributed power resource, update of high efficiency appliances, the aggregation of battery storage system and induction of consumers' energy-saving voluntary. PV cost drops as illustrated in Fig.1-18, indicating their increasing preference in predator sector. Government provides grants and subsidies for demand side management technologies, reached an agreement with power utilities to rapidly conduct competitive tenders to deploy smart meters with standardized direct communication functionality for customer. Meanwhile, launched an extensive electricity market reform. In order to incentive the uptake of high efficiency technologies and encourage customer more actively to participate in district grid operation management. Japanese policy makers are liberalizing retail electricity market to increase their economic efficiency and produce benefits for consumers mainly through price reductions Ref [43]. In order to reinforce industrial competitiveness, Japan has achieved full liberalization of retail electricity market in April 2016. policy makers opened the retail electricity market to competition to allow business consumers more options to manage their energy consumption, consumers can choose to buy electricity from retailers of their choices that best meet their needs, such as optimal tariff design, feed-in tariff and relevant capacity subsidies. Driven by the potential benefits from demand side management, HEMS (Home Energy Management System) is widely promoted to reduce household energy demand in the Japan national energy roadmap launched by METI in 2014. The subsidy and grant programmers for HEMS have been very successful leading to over 200000 units installed from 2012-2014. Housing developers have started bundling HEMS with their standard offerings to gain a competitive advantage. Together with offerings from ICT service providers, the HEMS market has now become sustainable without subsidies. Japanese government is devoting to the realization low energy consumption household, all new constructed houses are expected to be equipped with HEMS by 2030. The function of HEMS involves the real time control of on-site power generators and home appliances, monitors and revels the energy consumption, providing high efficiently energy supply resolution for customer, including space heating, cooling and hot water supply [44].

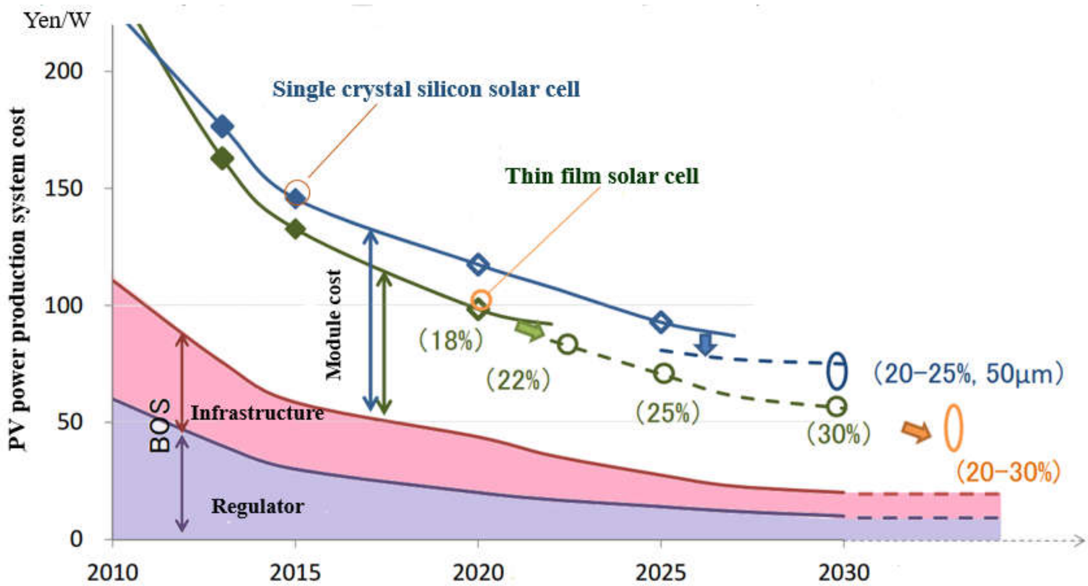


Fig.1-18. Cost trend of PV solar power technologies in Japan, reference: center for low carbon society strategy, 2015

1.4 Purpose of this study

The increasing integration of intermittent renewable energy sources in the grid has a significant impact on power supply the plan process, such as operational dispatch and grid flexibility. Simulation result will inform the strategy for managing the grid flexibility requirements created by growing renewable energy. There is a wide uptake of efficient energy system and all electrification trend in demand side. Demand response strategy becomes important, which can enhance the grid flexibility, help relieve grid constraints on the growth of renewable energy, and reduce the need for carbon-intensive back-up generation. Grid operator must look beyond simply the technology and recognize what extent consumers can engage in demand side management. Fig.1-19 presents the overview of participate objectives and structure of the virtual power plant, formed based on resources from both supply and demand sides.

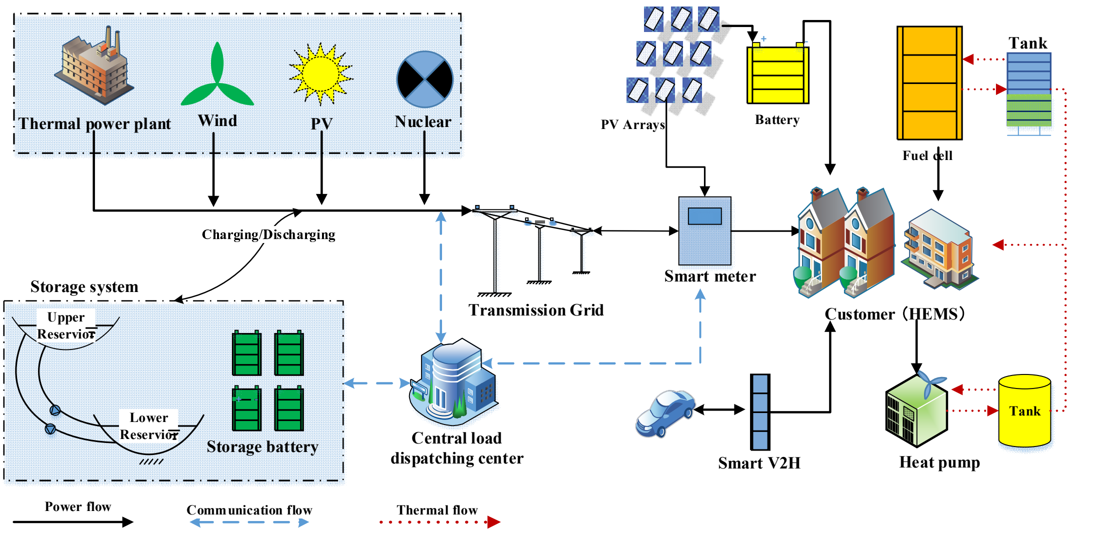


Fig.1-19. Research objectives and structure of power system in the thesis

Fig.1-20 depicts the main activities for load modeling and management in VPP architecture, including variable renewable energy production dispatch, grid load leveling via valley fill and peak cut, energy conservation and load shifting. In order to ensure a reliable and efficient operation of electrical grids, plant side manages the integrated variable renewable energy with help of large-scale storage dispatch. Additionally to the requirements that are posed by the integration of RES, the buildings sector is facing a trend towards decentralized, more efficient technologies to cover the electrical or heating loads. With increasing share of efficient power technologies installed in electrical distribution grid, their integration to the public grid needs to be planned similar to the integration of renewable energy resources. Customers participate in demand side management by offering flexible power and load profiles, through coordinate control of distributed energy resources, storage system and shift able activity or comfort based load.

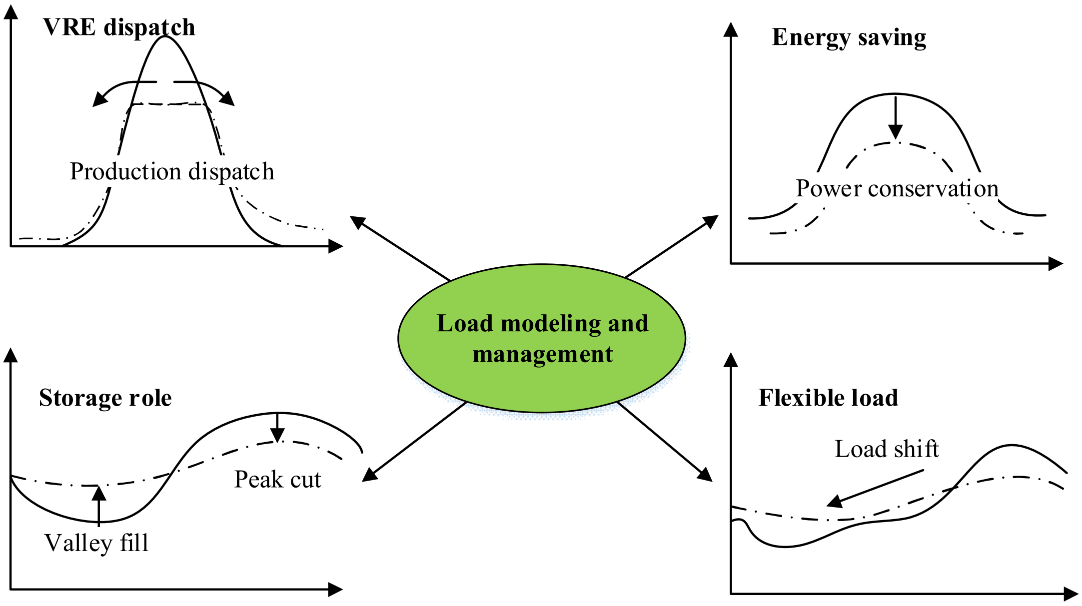


Fig.1-20. Main activities for load modeling and management in power supply-demand system

This study focuses on the optimization and evaluation of future power supply system with high renewable penetration level, taking into consideration of supply and demand resources. Provide meaningful insight for grid planner as they participate the growth of renewable energy resources and the strategies they should implement to meet flexibility requirement. Based on previous analysis approach and assessment study, the performance of efficient renewable energy integration and potential effects from demand side management are investigated, respectively. In addition, market experience and potential policy implication are introduced. The flow chart of this thesis is described in Fig.1-21.

- Background and purpose

In chapter one, firstly presents the worldwide situations of renewable technology development, then states the opportunities and challenges for power supply system with increasing variable renewable integration, provides the importance of coordinate demand side management. Finally illustrates the motivation and purpose of this research. In addition, the power supply situation in Japan is described and related studies have been reviewed.

- Methodology and approach

In chapter two, firstly the concept and approach for load leveling is introduced. Then previous research about impacts of renewable integration and role of storage system are described. Finally, the assessment approaches are reviewed, including residual load duration curve, screen curve method and evaluation for demand side management from bottom up approach.

- Feasibility analysis: A case study

In chapter 3, feasibility of Virtual Power Plant (VPP) in Chongming Island is investigated, VPP is constructed based on resources from both supply and demand sides, strategies focus on expansion of renewable energy and upgrade of home appliances in demand side. Analysis results verify the effectiveness of VPP concept based on cooperation between supplier and customer. The energy market structure is changing due to the application of the VPPs, benefits power plant industry and incentives users' participation in demand sides.

- Assessment in plant side

In chapter 4, assessment of renewable energy integration in plant side. The techno-economic viability of high variable renewable integration, grid flexibility and storage is investigated in this section. Firstly, electricity load and PV production in Kyushu Island are described. The impacts of increasing PV integration is illustrated in load duration curve. Storage dispatch is important for higher PV integration, PV-PHS dispatch scenarios are carried out based on simulation model with constraints, results indicate that pump hydro storage can play an effective role in promoting PV utilization via absorbing excess PV generation under grid flexibility limitation, PHS also effectively helps shave the peak load, enhancing grid flexibility. PHS effectively recovers the suppression and decreases the PV levelized cost of electricity especially under higher PV penetration, meanwhile shifts the curve of power supply merit order to right, decreasing the overall power generating cost. Increasing RES integration shifts power supply merit order curve to left and decreased the medium base load, PV-PHS can decrease the overall generation cost from 0.145$/kWh to 0.139$/kWh at 19% PV penetration, pumping ability to peak load ratio is 0.15.

- Analysis and evaluation in demand side

In chapter 5, performance analysis and evaluation of distributed energy systems. Firstly, introduces the motivation behind demand side management and illustrates the social demonstration projects in Kyushu. Then describes the tested high efficient technologies in the research. To get a better understanding of behavior of efficient power technologies based the real applications in social demonstration projects in Kyushu. Then investigated the cost saving and environmental benefits of decentralized energy systems in residential sector under current energy market. Combination of thermal storage and heat pump could be scheduled to lift the early morning valley period effectively. V2H brings more flexible option to the grid, aggregated EVs lifts valley grid load shaves the night period in absence of PV generation, potential cost saving and carbon emission reduction are achieved due to gasoline fuel consumption reduction. Generating ability of PV system shows great variation over months, the application of battery storage in residential PV system is investigated in detail. Aggregated PV-battery system can scheduled to increasing local self-consumption, meanwhile serve the grid for peak shaving. Relevant subsidies or further cost drop in battery is essential for the development of grid-supporting PV-battery system in residential sector. Cogeneration system (Fuel cell) operation highly depends on simultaneous thermal and power loads, power contribution shows limited contribution during summer or mid-season. 500 thousand participation of proposed efficient energy systems cut 8.8% peak load at 20:00 pm in winter, 2500 MW distributed residential PV system (4-6 kWp) can shave around 14% peak load during daytime in summer. The feasibility of CHP system is still highly dependent on access of direct subsidy due to high initial capital cost under current energy market, considering their potential flexible resource and carbon emission reduction chance. Scheduled distributed energy resources could shave the peak grid load to reduce the output from peak-meeting plant, further decreases the overall generation cost.

- Market innovation & policy suggestions

In chapter 6, market innovation and suggestions. From supplier perspective, the performance of dynamic price based demand response is investigated based on the social demonstration project experiment. The behaviors of change in daily electricity consumption curves can be obviously observed in types of consumer sectors under the designed CPP (critical peak pricing) event, their response effects are described and compared. From demand side management perspective, the integration of electrical technologies in demand side can provide flexibility to the public grid in a decentralized way. Reasonable subsidy or relevant incentive policy to grid-supporting power storage and residential CHP system is essential for their wider development considering their potential flexible resource and carbon emission reduction chances.

- Conclusion & outlook

In chapter 7, a conclusion of whole thesis is deduced and the future study about simulation and optimization of power system has been discussed.

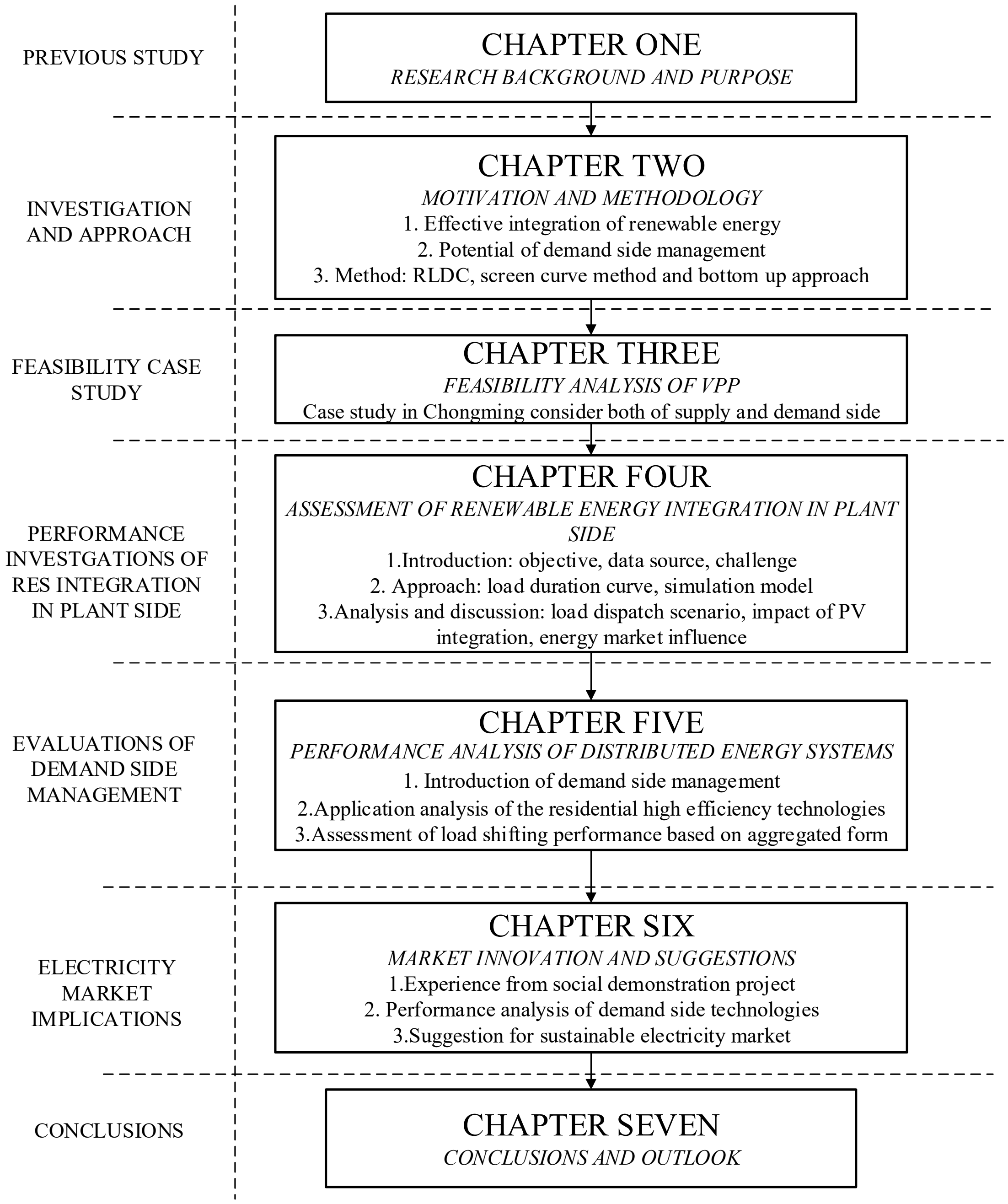


Fig.1-21. Research flow chart of the thesis

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Chapter 2

MOTIVATION AND METHODOLOGY

CHAPTER TWO: MOTIVATION AND METHODOLOGY

2.1 Motivation

Increasing renewable-energy penetration level brings promising environmental benefit and energy self-sufficiency security at district level, however the variable renewable energy (VRE) differs from the conventional power supply technologies, integrated intermittent output from VRE may present various challenges for grid operation, such as voltage control pressure, temporal power shortage or seasonal VRE surplus generation and storage capacity utilization. It is attracting a growing attention in current research, aim at improving grid stability and supporting the massive integration of intermittent renewable energy resources. Due to low correlation between fluctuating VRE generations and instantaneous electric demand, increasing VRE penetration level may result in a nonlinear decrease of residual load, even influence the regional VRE effective utilizations and market value [1-4]. Power demand presents variation from time to time in a day, meeting fluctuating demand especially during peak period pose great challenges to the electric utility. Small scale consumers account for a large ratio of national or district electrical energy consumption, practically changes in small scale consumption can be achieved via changes in daily life consumption habits and activity based load. Therefore, potential benefits could be achieved from load management efforts located in both of supply and demand sides [5-7]. Increasing grid flexibility by responsive demand is a central issue for the incorporation of higher levels of variable renewable energy. There exists significant flexibility in temporal patterns of appliances in demand side, it provide potential chances to achieve a social benefit via aggregated customer can participate in shifting load pattern corresponding to incentive energy market, Therefore, there are increasing number of research focus on grid load leveling and peak shaving via efforts from both supply and demand sides.

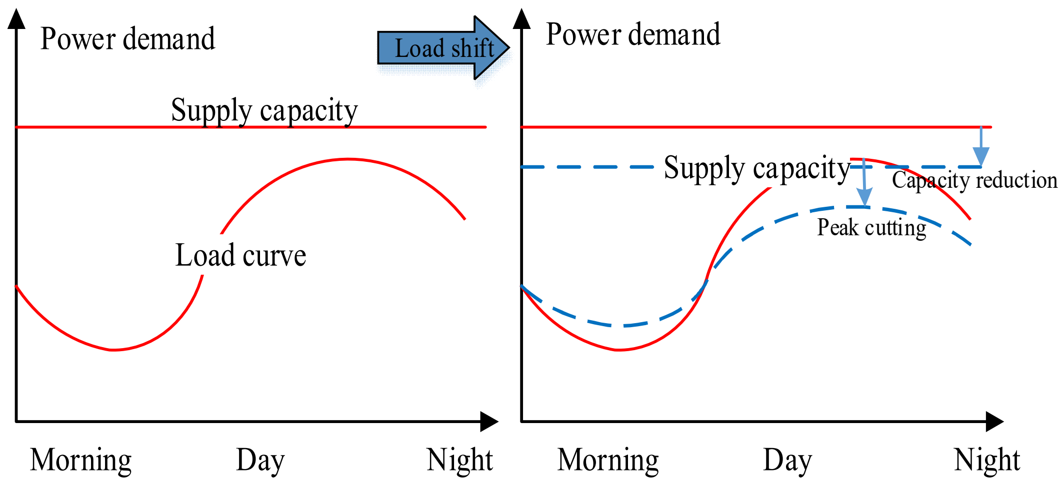

Fig.2-1. Grid load leveling scheme via valley up and peak shave approach

As shown in Fig.2-1, grid load leveling could be achieved by valley filling and peak cutting, uptake of storage dispatch system or aggregated effects of demand side response can effectively enhance the grid flexibility on daily basis, especially with variable high renewable energy penetration. For demand users, the overall operational cost can reduce due to the high price during peak period. For suppliers, benefits can be obtained through the investment replace of additional power generation facilities. In order to design a sustainable and security energy supply system, combined actions allocated on supply-side and demand-side need to be carried out.

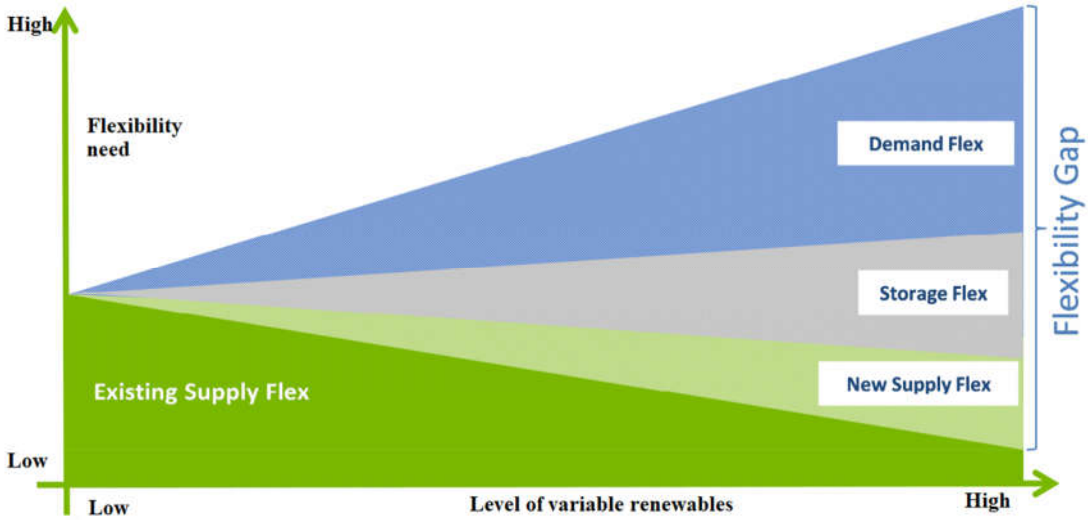

Fig.2-2. The emerging flexibility gap with different shares of VRS. Reference: ECOFYS, 2014

As described in Fig.2-2, variable renewable energy reduces the flexibility resources in the system by displacing traditional supply side flexibility providers while simultaneously increasing the need for flexibility due to their inherent stochastic nature. This creates a flexibility gap that will need to covered by new flexibility options. Options may come from in different forms and is relevant for various aspects of power system operation and planning, such as demand side flexibility, energy storage and new supply flexibility. Considering transition to higher penetration of variable renewable energy, the power supply-demand balancing should involve not only conventional generator operation on power side, but also the use of adjustable demand load such as the operation of heat pump water heaters or the charging of plug-in hybrid vehicles and electric vehicles. Such adjustable demand is expected to manage on the basis of day-ahead or real-time information of the demand-supply situation of a power system. In this research, main power load management strategies are illustrated as following:

1. Integration of variable renewable energy and dispatch of large-scale storage system in supply side (pumped hydro station).

2. Impacts of renewable integration on power system focus on effective utilization and grid flexibility.

3. Demand side management of grid connected distributed energy resources and power technology (PV, battery, EV and CHPs).

4. Load saving and shifting from coordinate control on flexible appliances in demand side (combined heat pump and thermal storage).

2.2 Literature review

2-2-1 Impacts of high RES penetration on grid

A number of research have explored the effects on the public grid from large VRE integrations in different regions. Ref [8] examined the changes to the electric power systems required to incorporate high RES penetration level in transmission constrained grid in Texas, US. Mismatch between simultaneously generation and demand, limitation of thermal generators flexibility may result in unusable renewable generation and increased cost impacts. Considering the increasing amounts of fluctuating renewable energy and its impact on grid flexibility, Ref [9] drew on the policy relevant scenarios for Germany, whereas yearly renewable surplus energy is low in scenarios analyzed, peak surplus can be high. Then stated approaches towards surplus generation challenges, such as decreasing the must-run of thermal generators, implantation of dispatch storage and making use of VRE curtailment. Ref [10] analyzed impacts of demand flexibility participation in spot and reserve markets, cost of reserve provision increases substantially with reduced baseload shares or increased VRE shares. Ref [11] evaluated optimum mix of electricity from wind and solar resources for New York State considering the limitation of pump hydro-electricity and grid flexibility constraints. Optimized synergy between solar and wind intermittent resources can reduce dumped energy to maximize the renewable energy penetration in grid. Ref [12] analyzing three major challenges of integrating variable generation from wind and solar into power systems: the low capacity credit, reduced utilization of dis-patchable plants and over production via residual load duration curve. Solar has a larger effect on the baseload, summer cooling demand drives the increasing capacity credit of solar PV. Ref [13] analyzed technical feasibility of fully renewable power system with the aid of hydro pump dispatch in Switzerland, significant pumped-storage hydro capacity provides valuable balancing and ancillary service for VRE management, the ideal PV fraction lies between 0.3~0.6 that requires the smallest amount of storage capacity and forced export and import appears acceptable.

The growing share of renewable generation will pose challenges to grid operators due to variable or intermittent nature. It adds variability and uncertainty in electricity supply, increases the number of flexible generators and requires additional reserve capacity to balance real-time production and supply [3, 10, 12, 14]. Further increasing renewable penetration may lead to renewable production curtailments without storage dispatch, due to grid flexibility limitation [15-18]. Curtailment rates versus penetration level of variable renewable production in grid. European saw dramatically growth of variable renewable energy in last decades, many studies suggests that increasing variable renewable penetration mainly come from wind and solar PV will lead to increased system operation costs, which could hinder the political feasibility or completely renewable electricity system. Germany has to curtail 3.7% of wind production at 12% penetration level, British wind farm appear to suffer around twice of curtailment of German at given penetration level 6% curtailment at 12%

penetration level, and the curtailment seems to increase at a steeper slope with increasing penetration. It should be noted that curtailment rates show great relationship with pattern of district demand loads and technology of integration management, China experienced 15% curtailment for a 3.2% wind penetration level in 2015 [19]. Increased integration and balance cost will result lower renewable energy market value as shown in Fig.2-3.

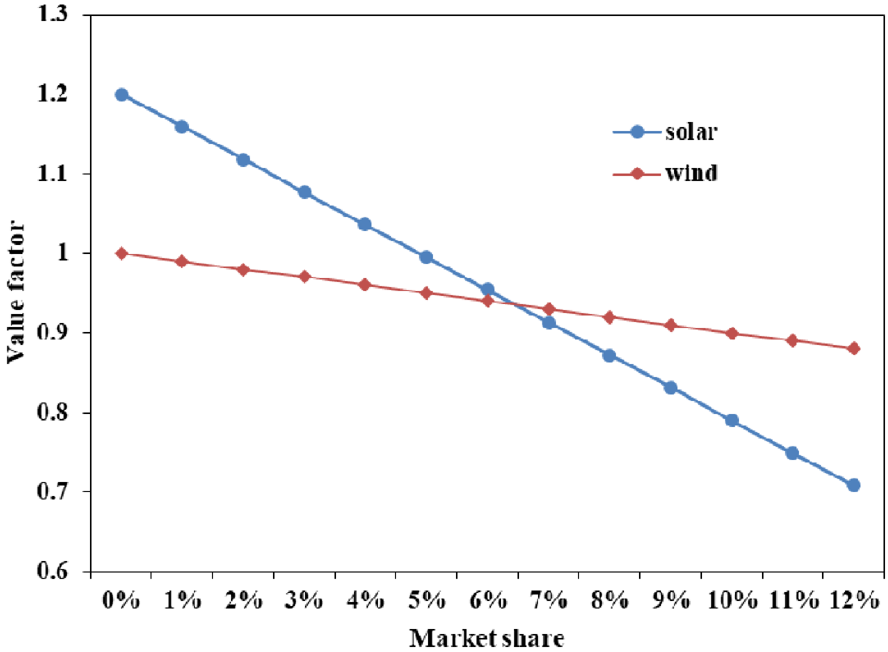

Fig.2-3 Market value of variable wind and solar in Germany from 2001-2015, reference: Hirth L **[4]**

Ref [1] provides a comprehensive discussion of market value of variable renewable energy, market value of renewable energy falls with higher penetration rate, results from literature review revel that wind value factors are close to unity and solar value factors are somewhat higher at low penetration level. Wind value factors are estimated to drop to 0.7 at 30% penetration rate, solar value factors are reported faster, drop to 0.7 at 10-15% market share. Ref [20] analyzed the impacts of wind and solar on grid flexibility requirements, growing wind penetration presents only minor correlation with increasing flexibility requirement, and appears to correlate with decreasing flexibility requirements in some instances, increasing PV integration might initially improve grid flexibility, however, further solar capacity growth develops a direct correlation with increasing flexibility requirements. Potential mechanisms that might reduce integration challenges like energy storage and demand side management.

2-2-2 Role of storage systems

Since demand is variable, the required instantaneous balance between production and demand is generally met by adjusting the output of flexible generator or storage dispatch. Various research discussed the impacts of high renewable energy penetration, storage system tends to maintain the value of variable renewable energy despite its variable nature, considering grid flexibility limitation. and optimal strategies are proposed to tackle the problem, such as dispatch of large-scale power storage system (hydro pump storage as shown in Fig.2-4) for peak shave, and active management on distributed grid connected renewable resources, focus on enhancing local self-consumption to reducing reverse flow [4, 18, 21, 22]. With increasing penetration level of variable renewable energy, increasing cumulative capacity of pumped hydro station is installed over recent years in worldwide [23, 24]. Ref [4] assessed the market value of wind power in power systems with hydropower in Europe, hydropower compensate for variability of wind power output, and mitigate a value drop by a third when wind penetration moves from 0% to 30%. As a result, market value of electricity from wind tends to decline at a slower rate if hydropower is present. Ref [25] examined the role of hydro pump storage to support solar energy generation while meeting the demand at various scale, results show that pumped hydro station can keep the diesel contribution to meet demand less than 10%, benefit is more significant in isolated system, current hydropower system could be converted to pumped hydro station without modify the upper reservoir. Pumped hydro storage system can help address solar intermittency problem, allowing for a greater capacity of integrated solar in the grid. In Ref [26] a combined wind and HPS 'virtual power plant' was investigated in island system, optimum PHS size is analyzed through adopting from both investor' perspective and RES penetration. The adopting operating policy and pricing principle have a great effect on optimal size of hydro pump storage project, Ref [27] presented a detail analysis of the levelized cost of storage for different storage technologies, result indicated that pumped hydro storage was considered as the cheapest technology for both long-term and short-term storage system. In Ref [28] a standalone hybrid solar/PV/battery system was presented, the effect of the capacity of RES and storage on system's reliability and economic performance were examined, results showed that size of components could great reduce via allowing some degree of unmet peak load, significant economic benefit can be achieved. The growing penetration level of solar photovoltaic technology is becoming a challenging task in Japan energy management, since the feed-in tariff launched in 2012, Japan are working on a project to build a pumped-storage hydro power plant to support the increasing renewable energy penetration, which targets at 22-24% by 2030. Fig.2-5illustrates a scenario of pumped hydro station in Kyushu, Japan.

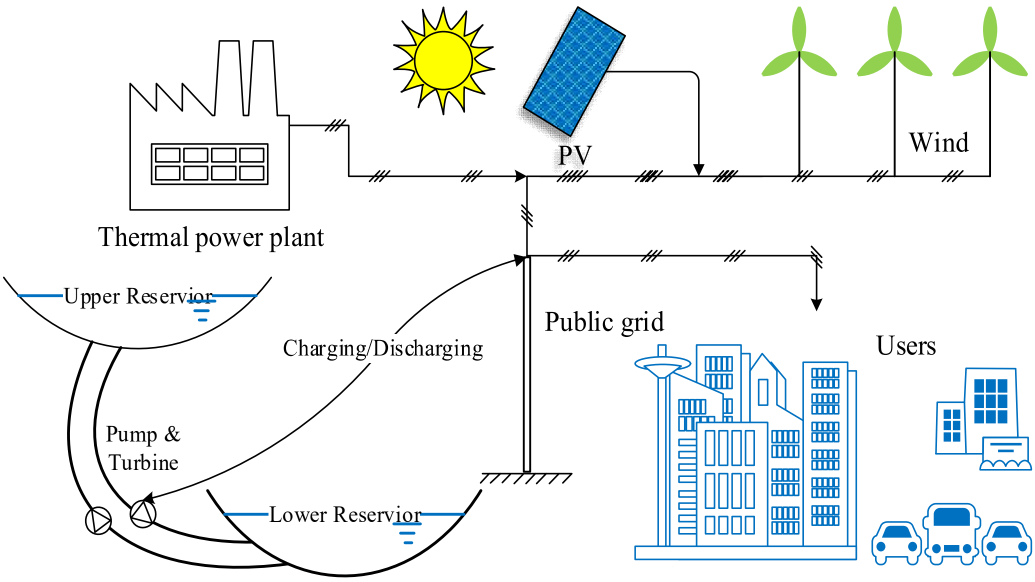

Fig.2-4. A structure of hybrid power supply system with aid of pumped hydro station

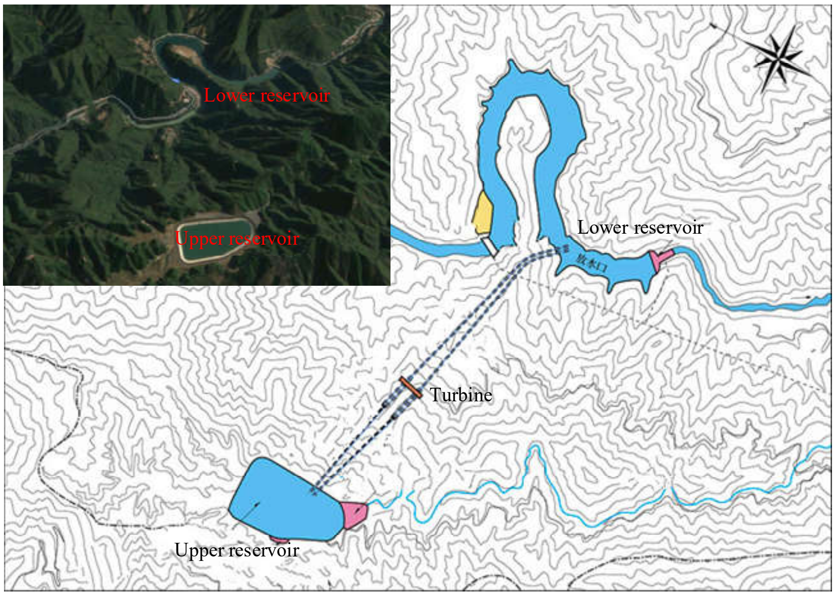

Fig.2-5. The layout of pump storage station in Omarugawa Disctrict, Kyushu

Increasing the self-consumption of PV system is an effective approach to integrate more district PV power in the power system, the profit for PV owner can increase and impacts of reverse flow on the grid will be reduced. Ref [22] proposed the scheme to share individual battery storages among communities, results indicate that feed-in power from community self-consumption rate obviously increased. Ref.[29] analyzed the benefits of battery storage systems in household with PV system and identified the effects on distribution and transmission grid in Germany. Results confirmed the persistence forecast management strategy was suitable for real-life PV battery system and exhibited a higher potential to relieve the stress on public grid by reducing the reverse flow fed into grid, meanwhile maintaining the PV self-consumption at high level. Ref. [30] quantified the self-consumption and economic performances of home PV-battery systems in cases of European countries, concluded that self-consumption and economic profitability were non-linear, as a function of the PV system and battery sizes, further decreases in battery cost or indirect subsidies are required for the uptake of Li-ion battery system. Ref. [31] implemented the linear programming to model to schedule the grid connected rooftop PV system under time of use scheme in California campus, they used the PV output and load forecast to determine the cycle of the battery, the NPV (net present value) of the battery array increased significantly through optimal storage dispatch schedules for minimizing demand charge. Ref. [32] presented the economic feasibilities of residential and commercial PV applications in Chile, their internal rate of return was calculated and presented by Geographic Information System supporting approach, economic profits increased under higher electricity price and larger self-consumption rate. Ref. [33] investigated the effects of EV charge-discharge and power interchange in smart house model in Tokyo, the improved performance of self-consumption ratio varied across the seasons, the rate of local consumption of PV output could increase 15% in summer, 15kg CO_2 emissions reduction per week on average was achieved by power interchange in community scale. Ref. [34] mainly analyzed the expansion plan for residential combined PV, battery and heat pump applications, that may steadily increase in residential sector in Japan, results clarified the optimal installation capacity over a twenty year period considering the changing condition of investment cost, incentive policy and electricity market. Simultaneously consumption and PV generation jointly determine the PV self-consumption rate Ref. [35], for higher direct self-consumption the greater energy demand should occur between around 10:00 am and 4:00 pm at the time of the PV generating ability is high. Excess generation will be either stored for later use or sold to the public grid directly, increasing reverse PV flows can lead to substantial net power demand changes in public grid, the daily variation during the summer or a transition season will be higher than ever experienced before, which will require more flexibility capacity and balance services, even decrease the PV market value Ref. [36]. Increasing grid PV penetration level also raise the concerns of utilities profit and integration limitation. Therefore, optimized control and schedule for distributed PV and storage systems are important for the benefits both of utility and customers, energy storage systems can contributed more to system level by regulating their charging/discharging cycle process. Ref. [37] developed the convex programming for optimal sizing battery of smart home considering real time pricing scheme, the size of battery and achieved revenue highly depend on the features of customer load profiles under off-grid condition. Ref. [38] developed a stochastic optimization for energy management framework of smart home with rechargeable battery and PV power supply, private electricity cost could significantly reduce via managing power flows of on-site energy resources under time of use tariff structure.

2-2-3 Potential effects of demand side management

There exists significant flexibility in temporal patterns of appliances in demand side, such as EVs and heat pump, providing an opportunity to utilizing demand side response solutions. Coordinate demand side management not only reduce the required generation or network capacity, but also facilitate the integration of RES through energy arbitrage and ancillary service provision [39, 40]. Demand side management could effectively help enhance the grid flexibility via improving the load pattern, for example to shift simultaneous loads to better match the power production. Research [41-45] examined performance of demand side management strategies, such as uptake of energy saving appliances, integration of flexible power systems, and relevant incentive policies encourage customers to actively participate in public power management and load shifting. Time shifting energy consumption practices in demand side provide potential chances for grid operators to lower the mismatch between production and demand profiles. To assess what extent does the shift in appliance objectives toward flexibility via corresponding demand side management strategies are clustered into three groups, including domestic cleaning activities, lighting and air conditioning, and cooking and leisure activities as illustrated in Fig.2-6.

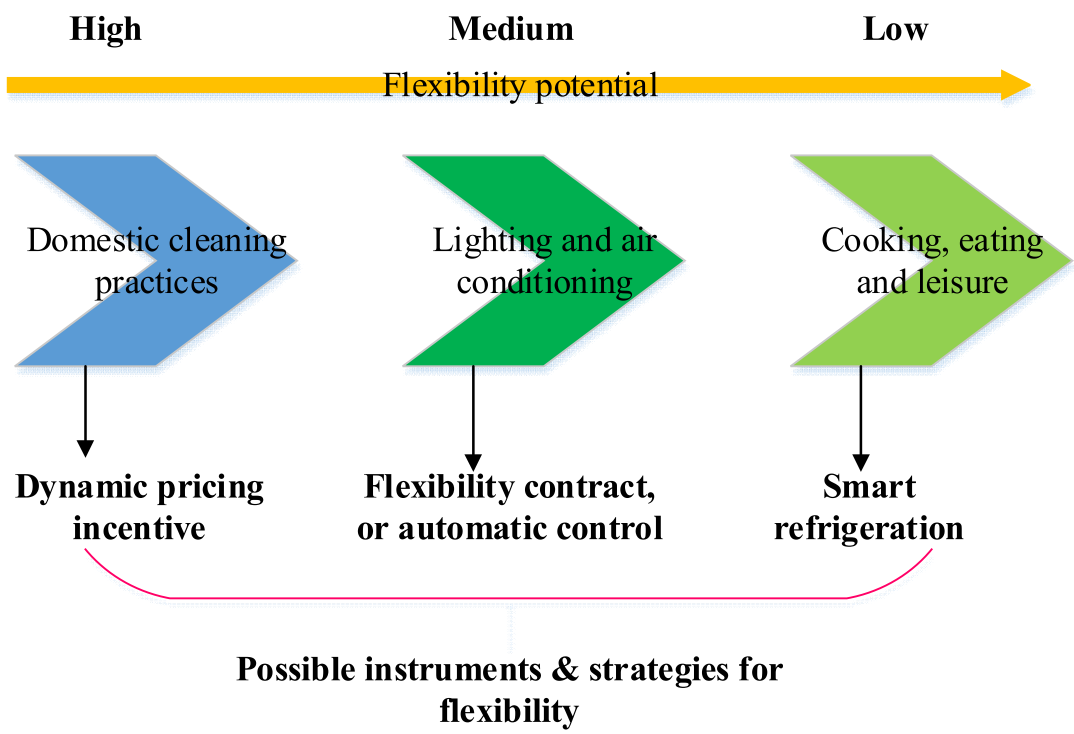

Fig.2-6. Flexibility of electricity appliances in demand side

Ref [45] indicates that the government-led, customer participation and business-driven will become the main features of future smart power grid in Japan. Relevant studies have discussed the load shifting performances via implementing high efficiency technologies such as heat pump water heater, distributed PV system and electrical vehicles (EVs) with demand response scheme. The popularity of heat pumps is supported by (designed electricity tariff scheme) energy market and policy implications. Heat pump water heater is generally considered as useful appliances for environmental protection and energy saving. Ref [46] indicates that electrification of heat sector may offer a vast potential of new forms of flexible demand, by time-shifting of heat production from heat pump system in buildings in Germany, achieving a reduction of system overall operating cost and environmental benefits. Ref [44] states that increase in energy price will enhance the selection rate of Eco-cute, cost reduction will be effective under specific tariff structure. Ref [43] analyzed the cumulative load shifting potential in heating and cooling sector, different flexibility and storage options can be used to alter the load trajectory. Ref [47] analyzed the effects of uptake of heat pumps in Great Britain national electricity grid from aggregated perspective, a simple upscaling method to add heat pump electrical load to national grid indicating peak demand increases and ramp rate increase. Ref [48] assessed the flexibility of the residential heat pump model considering maximum power, shiftable energy and regeneration time, results show that flexibility is highly dependent on ambient temperature. Ref [49] simulated the control models for heat pump and thermal storage, result indicated that customer with heat pump heating system can effectively participate in reduction of peak generation capacity. As the expansion of grid-connected on-site generators, distributed power resources provides customer potential benefit to manage their local power consumption under electricity market retail liberalization, meanwhile add additional flexibility to grid in aggregated form. Ref [50] examined an alternative option of creating power demand close to renewable sources in Japan rural area, instead of grid augmentation, renewable generation provides a significant merit for a sustainable future. Ref [51] pointed that lower rechargeable battery cost can decrease the PV output suppression rate after large-scale PV energy integrated into the grid. Ref [52] investigates the technical impact of future integration of electrical vehicles and PV generation, considering the residential demand and homogeneously distributed EV and PV, EV charging works effectively in valley hours, excess PV production will rise load unbalance degree. Ref [53] shows that EV aggregations can decrease their contribution to the system peak load, 24.8% decrease in the aggregate monthly bill is possible according to the time of use tariff scheme. Ref [54] investigates the techno-economic performance of interaction between MG operator and EV aggregator, vehicle to grid (V2G) and vehicle to home (V2H) behavior has allowed the coverage of demand peak, achieving lower total MG cost with regard to particular energy cost scheme. Ref [55] examined the potential financial return for using V2G as a grid resource for peak load reduction and regulation on daily basis, aggregated V2G participation may create formal storage market with higher penetrations of intermittent resources.

2.3 Methodology

2-3-1 Residual load duration curve approach

The ability of grid to accommodate VRE has a close relationship with the shape of demand curve, which highly determines the reliable operation to maintain a dynamic balance between electricity generation and consumption. The generator flexibility is defined as the portion of the annual peak capacity wherein power can be ramped up and down without needing to turn off any base-load power plants, it presents the capability of the power system to maintain reliability under VRE uncertainty. As a new source is added to the system, the power generated from that source at each point can be subtracted from the load at same time, the residual load duration is derived by sorting the residual load curve in descending time Fig.2-7 (left). The impacts of changes on utilization of dis-patchable plants, capacity credit and overproduction are usually assessed according to RLDC (residual load duration curves) [56-59]. Ref [12] using RLDC approach to evaluate the challenges of integrating variable generations from solar and wind, the low capacity credit, reduced utilization of dis-patchable plants and over production are presented using RLDC as illustrated in Fig.2-7 (right), results show that impacts of increasing variable energy can be substantial, independency of mix and region. Ref [57] uses RLDC approach to build Germany long-term energy-economy models, this RLDC approach allows improving the robustness and credibility of scenario results, such as mitigation cost estimates and role of variable renewable energy in low-carbon transformation.

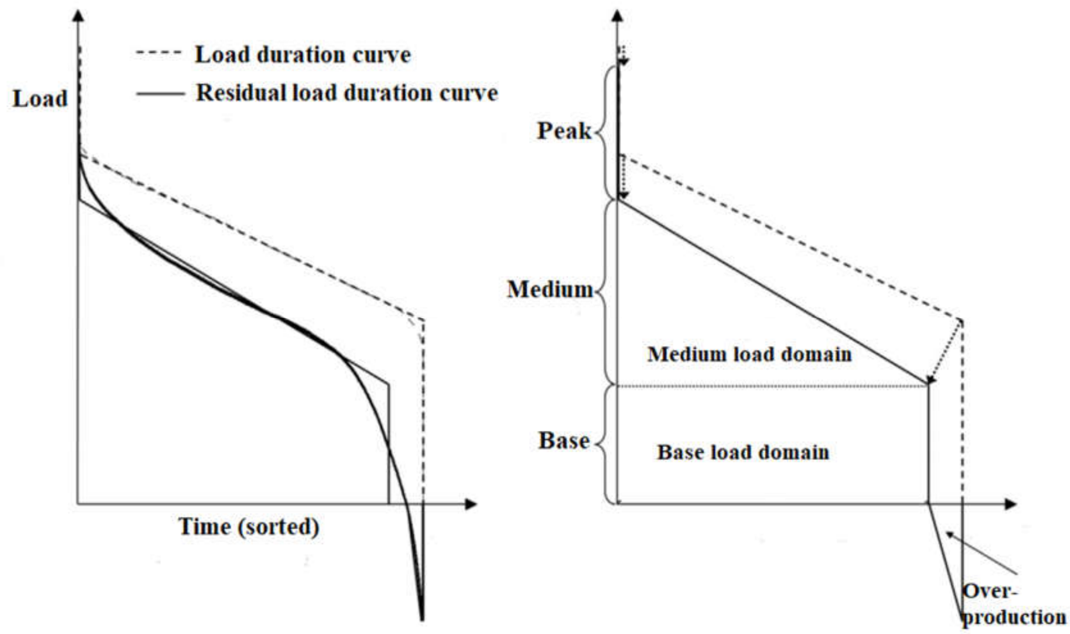

Fig.2-7. The RLDC is a approximated by a box and a triangle, four parts build the sorted load composed of peak, medium, base and over-production parts

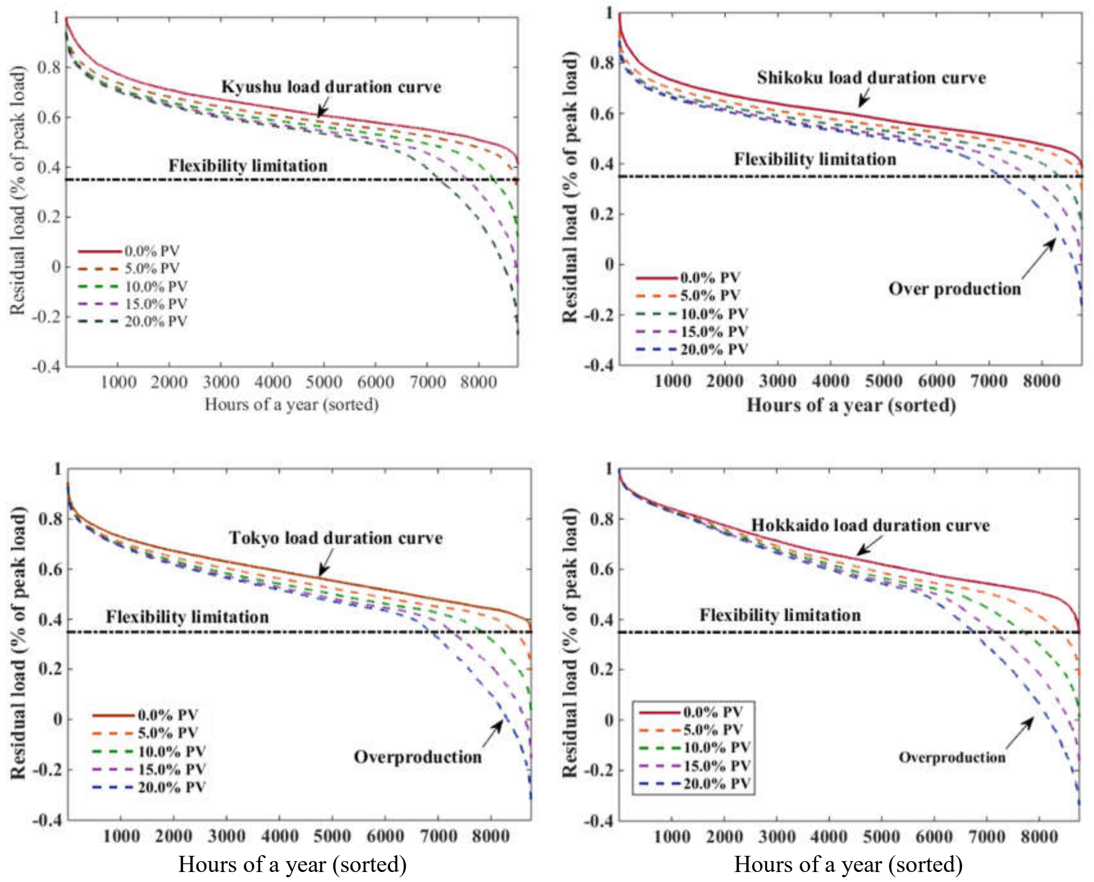

Fig.2-8. Residual load duration curves for different integrated PV capacities based on Kyushu, Shikoku, Tokyo and Hokkaido, grid loads and real PV productions in period of 2016.04~2017.03

According to the RLDC, the hourly electricity demand in MW for the entire 8760 h a year is depicted in descending order. The grid flexibility highly depends on the mix of its generators and largely constrained by the inflexible generators (nuclear, base-load plant). As depicted in Fig.2-8, the sorted residual load curves (normalized to peak value) of different districts, Japan were obtained by subtracting hourly simultaneous PV generations. Higher PV generation is scaled in linear with monitored district PV output, PV shows relatively low peak capacity and largely decreases the based load, it has resulted the grid flexible limitation. It is worth to note that the RLDC does not capture ramping and cycling requirements, since that would require the chronological order of the residual load, net load fluctuation from hour to hour will be lost in a duration curve, the overproduction will be larger considering the flexible limitation in medium load domain.

2-3-2 Screening curve methodology

The yearly cost per unit capacity for each power supply technology is a mix of capital investment, operation and maintenance (O&M), and fuel consumption costs. The combination of load duration curve and screening curve is applied to analyze the economic impact of variable renewable integration. The cost screen curve as a function of the number of production hours, and the slope presents the variable components including fuel, operation and maintenance. The screen curves are usually used to determine the cost efficient power supply system [56, 58, 60]. The screening curve cost method, originally proposed in Ref [60], serves to determine the optimal mix of power generating technologies to minimize overall supply costs. Ref [56] enhanced the method, provides a more comprehensive representation of thermal generation while keep screening curves well-known capability to provide valuable analytic insights on capacity expansion problem. Ref [58] uses the screening curve approach to evaluate the overall cost of energy system, originally proposed for electrical power system plan, and extended to address sizing of heating and lighting appliances.

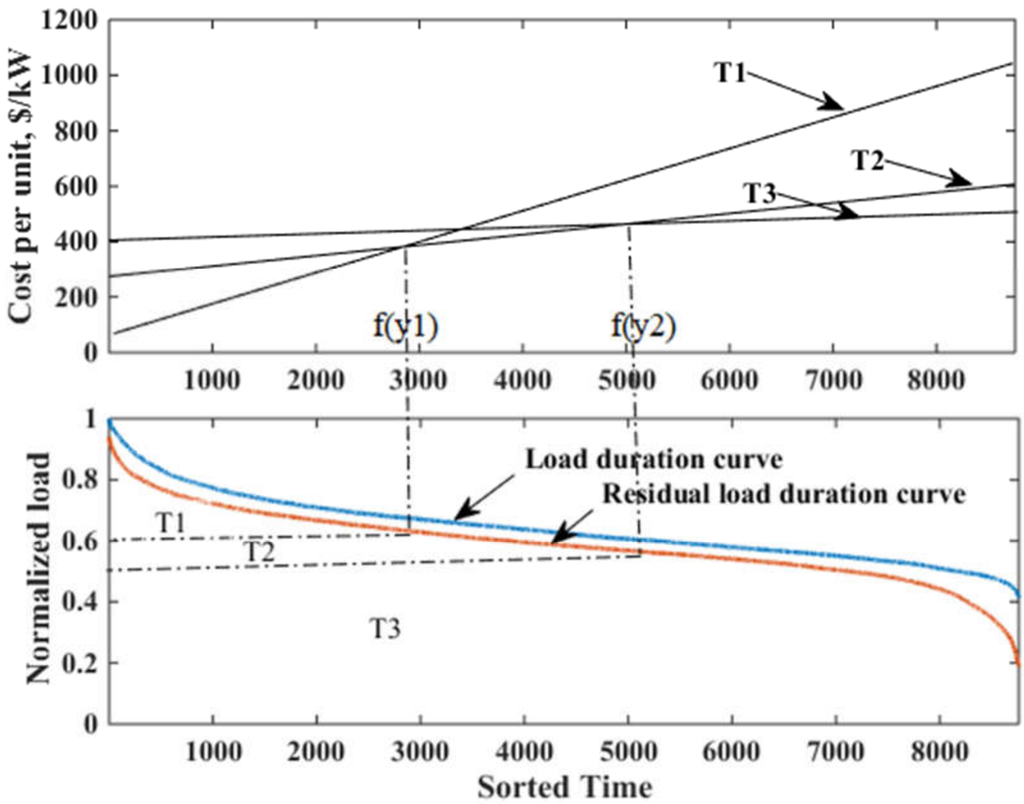

Fig.2-9. Typical screening curve method to analyze optimal generation mix

Variation of demand as function time is known as demand curve, utilities balance the supply and demand based on merit order dispatch that thermal units produce following a fixed merit order, which does not change with operating condition, and a unit can only work when all units that are earlier in the merit order are also producing. The screening curve and load duration curve allow to determine electricity prices and calculate contribution margin of power plants.

Fig.2-9 illustrates the yearly total production curve per unit power generator as function of operation period, the cost function Eq.2-1 forms the cost curves of technology presented in Fig.2-8. At lower value of operation time, the annualized capital cost dominates overall cost, technology features with higher variable cost increases more with increasing operational time. Let y units of installed capacity met by technologies T1, T2 and T3, the intersections of three curves determine the number of hours of production that separate the annual regimes where the technologies (T1, T2 and T3) are optimal.

$$C_{tot} = F_1 * y + V_1 * \int_0^y f(y)d(y) + F_2 * (1-y) + V_2 * \int_y^1 f(y)d(y) \quad \text{Eq. 2-1}$$

The overall objective is to meet power demand at minimum overall cost, when the total annualized cost is minimum.

$$\frac{d(C_{tot})}{dy} = 0 \quad \text{Eq. 2-2}$$

Differentiating the equation, we get:

$$F_2 + f(y) * V_2 = F_1 + f(y) * V_1 \quad \text{Eq. 2-3}$$

The variable costs accounts for the variable component of operating cost and is expressed as cost per unit load supplied. The annualized fixed costs F_i are expressed in term of unit cost, total capacity cost of each technology is a linear function of its capacity. Similarly, the variable costs V_i accounts for the variable component of operating cost and is expressed as cost per unit load supplied.

It should be noted that generation costs have a close relationship with load profile, it influences the optimal mix structure, economic schedule and plan of power technologies. Meanwhile, added variable renewable energy profiles form a new duration curve as presented in Fig.2-8, there are generally leading a greater reduction in medium production from conventional thermal plants.

2-3-3 Bottom up approach for demand side management

The residential sector accounts for a major portion of social power consumption, however, it remains as an uncharted and unattended. Modifications in power consumption pattern of small-scale customer can have a great impact on aggregated demand. Bottom up approach is widely developed to identify the contribution of end user, and modeling small-scale consumption based on customer's activity and comfort contexts [61-66]. For example, end user shifts thermal load via combined heat pump and thermal storage system, transform heat demand into electric consumption during off-peak period in response to the electricity price changes over daily period.

Under feed-in tariff scheme or relevant incentive subsidies, there are rapid development and uptake of renewable sources and distributed power technologies over recent years. It is widely expected that distributed energy resources capacity additions in form of physical infrastructure, such as PV, generator, dispatchable energy storage and electric vehicles will play an ever greater role in future power supply system[52, 65, 67, 68]. Increasing grid connected distributed resources and relevant local governance are expected to play increasing roles in management of community power system. Various forms and innovations are proposed to explore future structure, opportunity and challenges of future energy supply system with participation of distributed power systems, such as virtual power plant, peer to peer trade, smart micro grids and community scale energy system. For example, the daily PV production usually shows a low correlation with customer load profile, grate excess power flow may be sold to grid, resulting fluctuation in grid voltage.

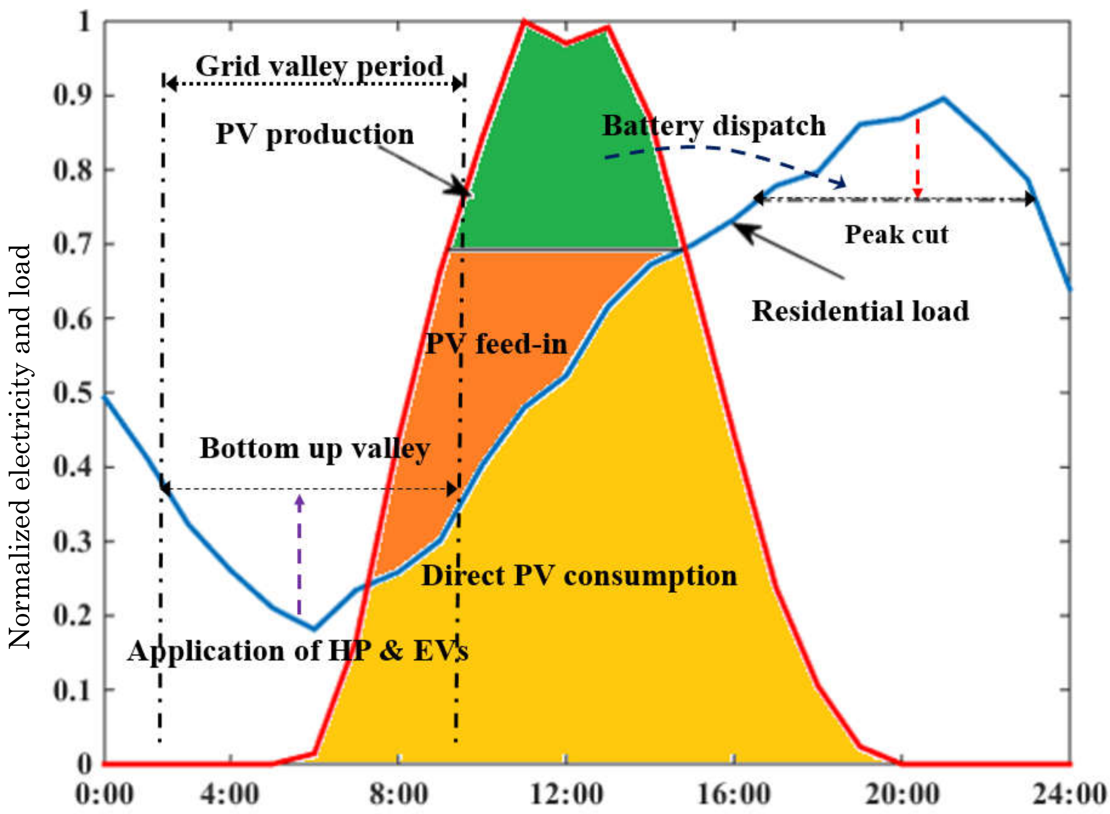

Fig.2-10. Schematic representation of demand side management from bottom up modeling approach

Fig.2-10 illustrates schematic representation of residential demand side management from bottom up modeling approach. It can see that PV production (red line) focuses on daytime and shows low correlation with residential load profile (blue line), there is a mismatch between consumer load and local generation. And customer tends to consume less during grid valley period (early morning). Uptake of battery storage is expected to play an effective role in enhancing local self-consumption, stores PV generation during daytime then releases stored energy for night peak shaving, lessen impacts to the grid. The role of proposed storage systems and on-site generator in Fig.2-10 can be described as following:

- Heat pump operates to produce hot water during lower pricing period under time of use tariff scheme, transforming electricity to thermal energy. As a result, time-shifting of heating production is achievable without compromising the levels of comfort for inhabitants.
- Charging period of EVs is generally set during the valley period, replaces part of gasoline fuel consumption, then EV discharge stored energy to home during night period for peak shave, enhancing the grid flexibility on daily basis.
- PV-battery form enhances the local PV self-consumption, aggregated battery can be used as active power resources.

Aggregated consumption of heat pump water heater and EVs will lift the grid valley load, EVs and PV-battery can participate in peak grid shave. Overall, the cooperation intersection between residential customer and utility could result the energy saving and load leveling from coordinate optimization and management. Meanwhile, stabilize the grid energy supply and provide chances for installation retrofitting or high efficiency appliance upgrade. In this thesis, the bottom up modeling approach generally focuses on the following aspects:

- Real time control of on-site generators, and grid-supporting modeling of local power integration.
- Coordinate integration of energy storage (thermal tank and Li-ion battery), changes in load pattern based on demand response strategy.

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Chapter 3

FEASIBILITY ANALYSIS OF VIRTUAL POWER PLANT

CHAPTER THREE: FEASIBILITY ANALYSIS OF VPP

3.1 Introduction

The sustainable development of the isolated islands usually faces a balance between the economic benefits and increasing energy demand. Especially small island developing states or small islands usually suffer from high costs of imported electricity and external shock. Although a considerable amount of study has discuss the sustainable development of the small island country, there does not exist a potential way to relieve the power supply pressure for the island considering both of plant and demand sides [1-3]. A sustainable power supply framework should fit to the condition of the region, it may be a better choice to increase the power self-support through multi power flows and management strategies, such as constructions of distributed renewable power generation and update of high energy efficiency appliance in buildings.

In order to increase the sustainability, the combined actions allocated in both supply-side and demand-side need to be carried out according to the local resources and constraints. Recently, the integration of distributed renewable energy resources has been introduced as an effective way to address the power shortage and minimize negative environmental impact. However, the increasing proportion of electricity generated from renewable resource will also pose challenge to the grid reliability due to its natural stochastic fluctuation. The household and tertiary industry buildings are expected to account for a significant ratio of future electricity demand, uptake and use of high efficiency appliances is another promising technology to tackle the increasing electricity demand in buildings [4-6]. Energy saving measures for HVAC and lighting systems have energy saving potential of 20% or more according to the previous publication [6].

Development of distributed renewable energy resources and aggregated electricity saving strategies in buildings can jointly play positive roles in future efficient electricity supply-demand balance framework, especially for the island or district faces a great challenge of the energy shortage and carbon dioxide emissions reduction target. The integrated distributed power resources and energy saving technologies implemented in the buildings can be seen as an equivalent efficiency virtual power plants (VPPs) in society. Meanwhile, it has to note that different market scenarios and outcomes will come out after the construction of the VPPs. However, research thus far has less assessment on this type of efficiency VPP concept. Therefore, the feasibility and assessment of this VPP need to be deal within detail, considering its impacts on both the conventional power plant and demand sides, such as electricity saving, emissions reduction, payback performances.

The technical potential of power energy saving is the consequence of plant-side and demand-side characteristics. This chapter focuses on the feasibility study of the VPP in Chongming Island, China. Main objective in this study is to explore the application feasibility and performance of efficiency VPPs based on the exploitation of local renewable energy resource and the energy conservation efforts among demand side.

Structure of this chapter is as following: scope of the renewable energy resource in the islands, the economic performance of renewable power units, identifying the energy saving potential in the buildings, confirming power saving performance of the implemented appliances, economic saving benefits by determining the return on investment from the efficiency VPPs under different market scenarios. Provide policy makers with reference results to assist the form of VPPs in the islands.

3.2 Objective and data

A brief introduction about the electricity power industry in Chongming is given in the following section, mainly includes the geographical scope, power supply and demand condition in this Country.

3.2.1 Geographical scope of Chongming

Chongming Country is mainly made up of three islands, Chongming, Changxing and Hensha, covering 1411 km2. As shown in Fig.3-1, Chongming is the largest alluvial island in the world and third largest island in China, located in mouth of the Yangtze River, dividing the river into northern and southern channels immediately prior to its entrance into the East China Sea. The island forms the northernmost part of the municipality of Shanghai, which has been connected into Shanghai by the bridge and tunnel. The Country is situated within the north subtropical monsoon climate, annual average temperature is 15.8 ℃ with abundant of natural resources (solar, wind and biomass). In 2010, it had been chosen as one of the three low-carbon demonstration areas in Shanghai, planned as an eco-island for future development, aiming at becoming a center for tourism, ecology, scientific and technology. According to Chongming Annual Statistic Bulletin (2016), the population of this Country has reached 672309 by the end of 2015, however, it is experiencing a negative growth rate -0.549% and the GDP (Gross Domestic Product) reached 291.12 billion with growth rate of 7.0%.

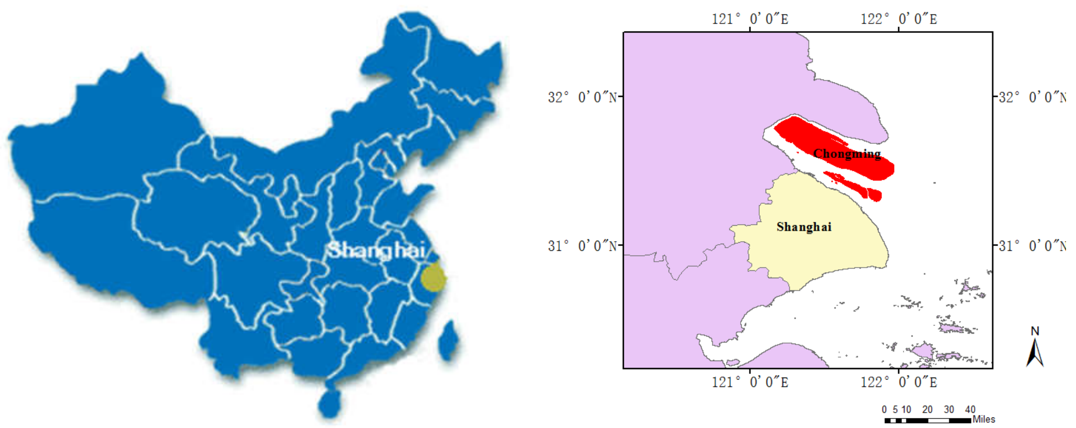

Fig.3-1. The objective geographical position of Chongming Country

3.2.2 Power supply and demand

As the largest economic center of China, Shanghai emits a large amount of greenhouse gas (GHG) emissions and is still expected to experience a repaid economic growth period, the building sectors are estimated to experience a further increase in the ongoing decades, so the power demand will likely expand to some degree. In order to deal with the conflict between economic growth and sustainable development, as show in Fig.3-2 the government invested significant cost in terms of human resources and capital, mainly including the construction of power plant and transmission lines (7). Long-term planning strategies for expansion of supply options is essential for the increasing electricity demand, the local government has announced a series of incentive policies, such as renewable energy resource subsidy, higher feed-in tariffs and carbon tax, to encourage the development of distributed energy systems (DES). Make sure that investment in renewable energy resource could yield stable and sound profit, fostering its stronger market competitiveness than conventional power plant.

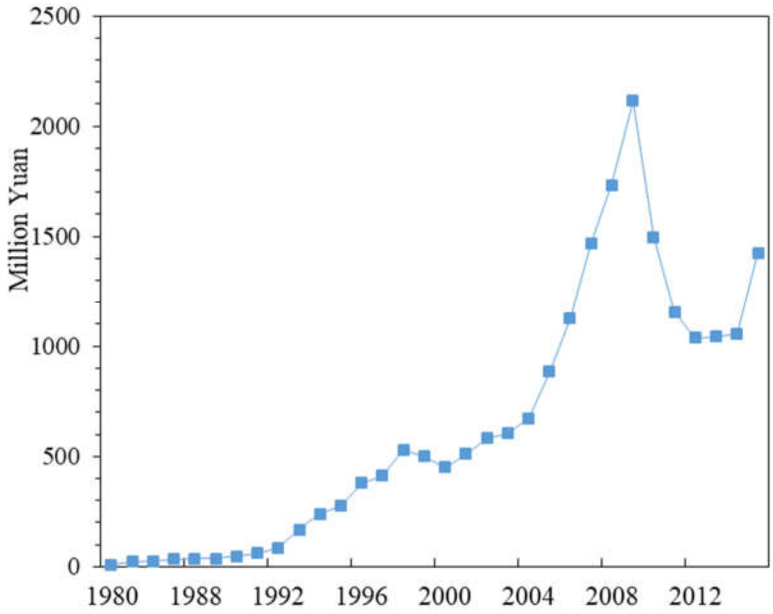

Fig.3-2. The yearly electrical power plant investment trend in Shanghai

Chongming country as the least developed region in Shanghai has experienced rapidly development in recent years. The electricity self-supply and demand in Chongming from 2008 to 2015 is illustrated in Fig.3-3 according to the Annual Statistic Bulletin, Chongming (2016), the whole year electricity consumption reached 2405GWH with the self-production power 269GWH in 2015. The peak electricity demand is expected to increase from 487MW in 2014 to 737 MW in 2020. In view of balancing the high speed economic development and environmental conservation, a target of 20% reduction in energy intensity is proposed in the outline of ecological island construction in Chongming (8). Since 2009 the government has shut down some small based on coal or oil fired power plants, which caused the reduction of electrical power self-support as shown in Fig.3. However in order to achieve a sustainable development, strategies are not only need to reduce GHG emissions, but need to establish a sustainable framework for the power generation system to meet the increasing electricity demand.

As one of the main wind energy resource regions (Chongming island, Changxing island, Hengsha island, the Nanhui district and the Fengxian district) in Shanghai, wind power plant makes a great contribution to the Chongming district power production. Nowadays the main local electricity power generation in Chongming Country includes: total capacity of 291MW wind farms, 24 MW coal-fired power plant, others (small coal or oil fired boilers) in 40MW capacity. About 80% external electricity demand imported from the neighboring Jiangsu Province, the proportion of electricity based on the coal consumed power plant is considered to be about 81.2%, with the electrical efficiency 321g standard coal per kWh.

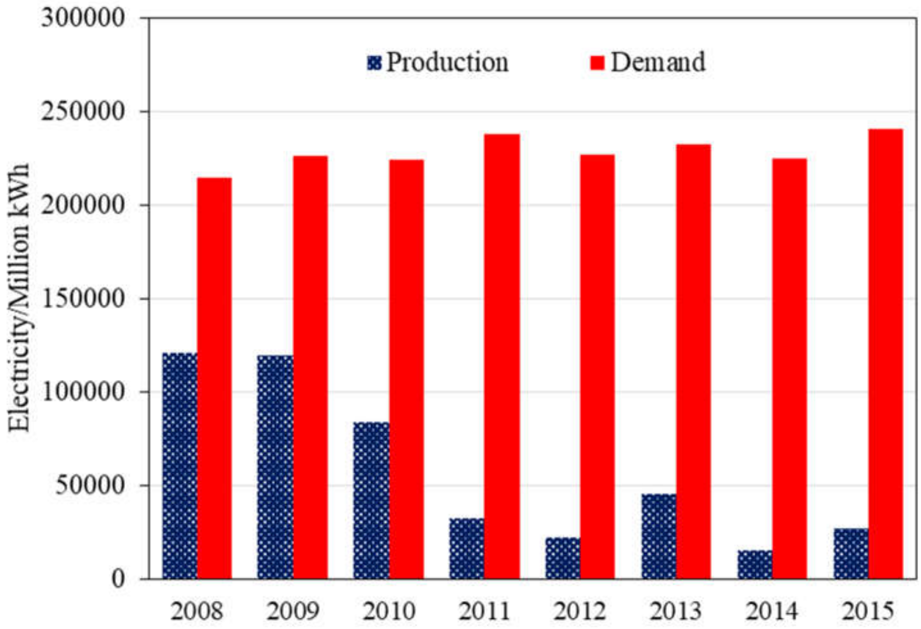

Fig.3-3. Power production and consumption in Chongming

Fig.3-4 presents the information of energy consumption structure per industry from 2008 to 2015 in this country. The electrical power consumption of Chongming mainly includes: primary industry (such as farming, forestry, animal husbandry and fishery), secondary industry (such as manufacturing industries and the construction sector), tertiary industry (such as transportation, storage, post and communications, wholesale, retail sales, catering, trade and others) and households. It is obvious that the secondary industry contributes to the largest percentage of power consumption, however it had decreased from 77.6% in 2008 to 61.6% in 2015. According to the statistical data, the trend of power consumption in secondary industry has become stable approximately 1600 GWH per year since 2013. The electricity consumption in household and tertiary sector shows a slow rising ratio in the social electricity consumption and is expected to experience an increasing period in the future. As estimated the electricity demand will reach 1055 GWH by the end of 2020, accounts for 39.8% in the whole society.

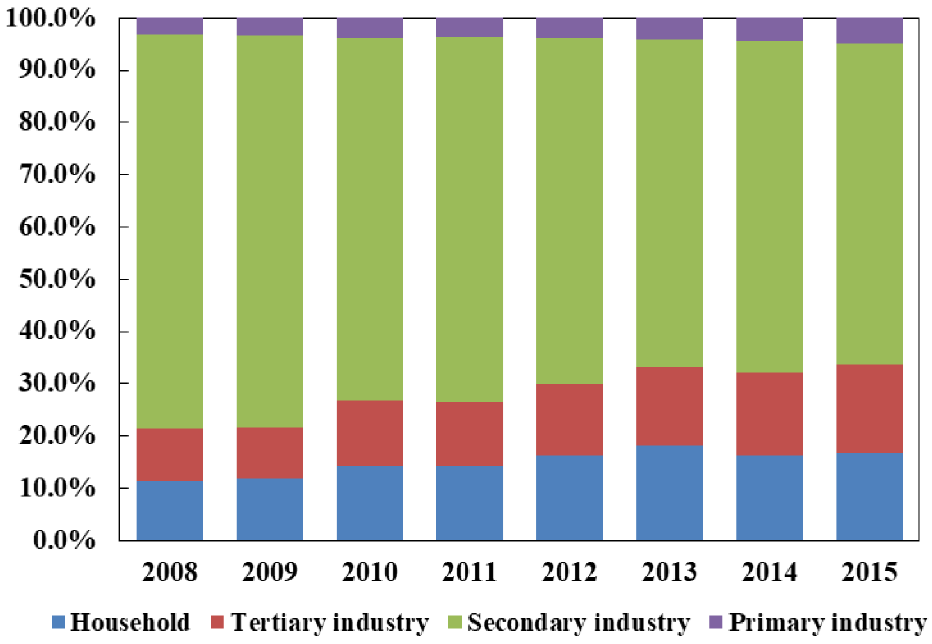

Fig.3-4. Structure of electrical power consumption per industry

3.3 Approach method

3.3.1 Power generation technologies in plant side

The utilization of renewable resources can not only release the pressures of GHG emission reduction and local air pollutants, but will also increase the power self-sufficiency ratio and power dependency in the islands. Now present renewable energy utilizations still accounts for a small ratio of the total electricity demand in this country. In order to achieve the planed scope of eco-island in Chongming, distributed renewable energy power units will play an important role in the future sustainable electricity supply framework, the renewable penetration in the public grid will increase further. In addition, a broad application of renewable energy technologies is favorable to the security and diversity of power supply. A better understanding of the local renewable resources is essential for the power sustainable development. In the following section we will firstly classify the main available natural resources (wind, solar, biomass) in Chongming Country.

(1) Wind

Chongming island is among the most abundant wind power resource in China (2), according to the weather parameters, the annual wind direction is comparatively stable and distribution of wind energy is comparatively concentrative. The annual mean velocity reaches 7.0 m/s at 50m altitude in Chongming, the annual mean density of wind energy is 340 W/m2 and annual effective and available time of wind energy reach 8418 h and 2200 h respectively [16], which provides a great potential for the exploitation of wind energy. In addition, the wind power plant shows relative lower capacity cost compared with other renewable resources. According to the 13th Five Year Plan Shanghai (2016–2020), the government will further expand the capacity of wind power plant in Chongming Country.

(2) Solar

The solar radiation on Chongming Country is abundant, annual average utilized time is about 1100 h, with average annual solar radiation 4700MJ/m2, the whole year solar radiation is about 1.57 million GWH according to the primary estimation. There is a potential to reduce dependency on power import and share peak load for the public grid. Nowadays, the installed capacity of solar power plant in Chongming Country is about 4.8MW includes: 0.8MW grid-tied household PV system, 20 enterprise PV power plants 4MW, with the power production 5020MWH per year approximately. Currently, solar water heater equipment is the most advanced and economical feasible technology, the area of the solar thermal collector has reached 160 thousand m2 in Chongming, thermal utilization ratio is about 35.0% [9]. Now the restricting factor for solar energy electricity power generation is mainly its high investment cost and intermittent characteristic.

(3) Biomass energy

Chongming is an important agricultural area in Shanghai, there is about 50500 ha farmland in 2015. Assume the heating value of residues is 18.6 MJ/kg, total energy potentials of agricultural is about 4500GJ/year. Considering one-third is used for disposed, one-third is used as livestock feed. The left agricultural straw and livestock manure could be used to fuel a biomass power plant, the generated electricity is estimated 440GWH and 600 GWH. In addition, compared with the large-scale power plant, the small distributed generation fuel by biomass gas are suited to the island due to their low investment, shorter construction period and maintenance cost.

There is a great potential of utilization of renewable power resources as depicted in Table3-1 to increase the local power self-support ratio, in order to increase the renewable generation penetration in the public grid, it is essential to carry out its economic performance in the power supply framework.

Table3-1 The demand load and available energy resource in Chongming [1,2]

Electricity demand		3200GWH
Peak power		737MW
Solar[a]		1.57×10^7GWH
Wind[b]		3000GWH
Biomass	Agriculture biomass	440GWH
	Livestock manure	760GWH

Annual effective utilization: a-1100h, b-2200h

3.3.2 Power saving potential in demand side

Electrical customers can reduce electricity consumption by updating the advanced efficiency appliances in building side, such as lighting, air conditioner and refrigeration systems, that account for a great power consumption ratio in buildings. Considering the components of social power consumption in Chongming, power saving potential via updating high efficiency appliances in household and tertiary industry sector will be calculated in this part. The detail results are summarized in Table 3-2. Power consumption reduction through improving electricity efficiency of the appliances can be seen as the virtual power plants (VPPs) formed among the aggregated buildings in demand side.

$$Demand_{save} = Demand_{ac} \cdot Save_{p,ac} + Demand_{ref} \cdot Save_{p,ref} + Demand_{lig} \cdot Save_{p,lig} \quad \text{Eq.4-1}$$

$$Demand_{total} = k \cdot Cap_{plant} \quad \text{Eq.4-2}$$

$$Demand_{save} = k \cdot Cap_{vpp} \quad \text{Eq.4-3}$$

Demand presents the electricity demand, *ac*, *ref* and *lig* are abbreviated form for air conditioner, refrigerator and lighting system respectively, $Save_p$ presents power saving potential for appliances, Cap_{plant} is the capacity of conventional power plant, Cap_{vpp} is the capacity of virtual power plant. By 2020, the peak power demand will reach 737 MW to meet total demand 3200 GWH/year. The annual power consumption in household and tertiary industry sector is around 1055 GWH depicted in Section 2.2. As shown in Table3-2, saving potential is the sum of electricity saving located in each part around 273 GWH/year. In order to evaluate the electricity saving benefit brought from the update of high efficiency appliances, Fig.3-5 present the potential energy saving amount from high efficiency appliances. Meanwhile assumed that the maximum capacity of the conventional power plant equals to peak power demand and has a linear function of the total annual electricity demand, *k* is linear coefficient. The calculated virtual power plant capacity is equivalent to a 63MW capacity of the conventional power plant in 2020 scenario as shown in Fig.3-6 according to Eq (1-3).

Table3-2 Electricity consumption ratio and saving potential in household and tertiary in Chongming [5-7]

Type	Air conditioner	Refrigerator	Lighting	Others	Total
Consumption Ratio	36	25	13	26	100
Amount (GWh/year)	380	264	137	247	1055
Saving Potential (%)	33	30	50	n-a	25.9
Saving (GWh/year)	125	79	69	n-a	273

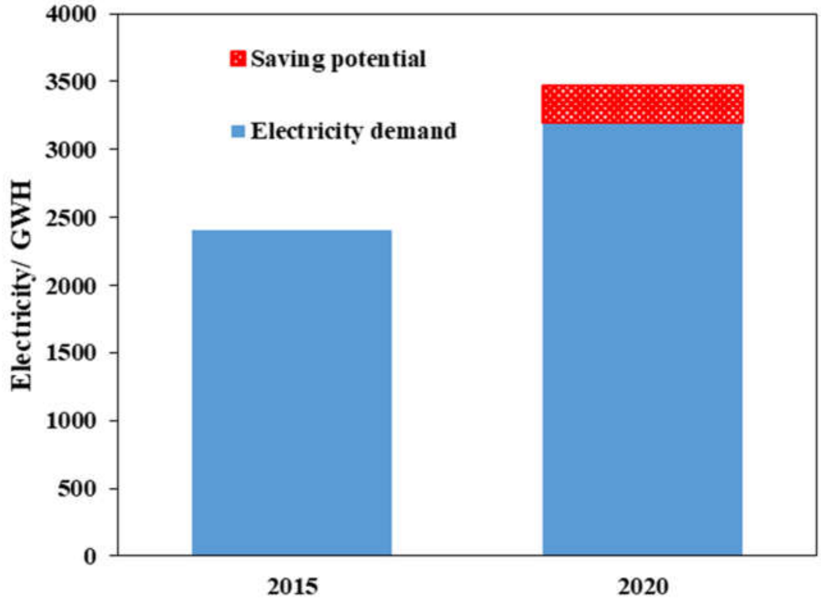

Fig.3-5. Potential annual power saving amount

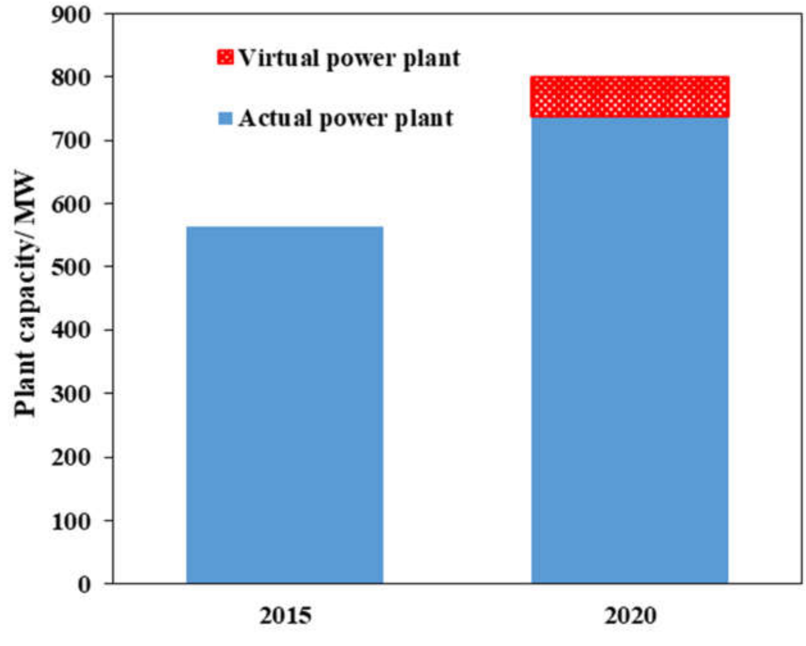

Fig.3-6. Potential capacity of virtual power plant in demand side

3.4 Analysis and results

3.4.1 Plant side analysis

In the following section, the return on investment of the renewable energy power generation and update of effective appliance technologies in buildings will be discussed by using payback analysis and life cycle cost analysis respectively, thus the VPPs implemented feasibility will be carried out mainly considering the economic benefits brought to both of the plant and demand sides. Analysis includes recently average utilization hours of the conventional coal based power plant 4330 h in China, the annual effective utilization hours about the renewable resources.

In the flowing, analysis model mainly includes the installation, operative and maintenance costs of the renewable power unit, as well as incentive strategies by the local laws and regulations to build economic driver for the implementation of efficiency VPPs. The payback period (PBP) of each component in the efficiency VPPs is calculated by setting to zero the NPV (net present value) of the total investment, considering the cash inflows (R_j), outflows **(** C_j **)** for the generic year j=[1,2,…,n] and n is the number of year in the payback period.

$$NPV = \left[\sum_{j=1}^{n} (R_j - C_j)(1+i)^{-j} \right] - C_0 \quad \text{Eq.3-4}$$

Choosing an interest rate i equal to 4%, we calculated the number of years for renewable power units NPV=0 individually in Eq.3-4. The total annual cash outflow consists of the initial capital cost C_0, operation and maintenance cost C_j. The cash inflow refers to the profits from sold electricity.

The existing incentive policy for the renewable energy resources sold to the public grid [$/kWh] are 0.15, 0.09, 0.11 for solar PV, wind and biomass plants respectively, the electricity feed-in tariffs of the conventional power plant is 0.066 $/kWh. According to the reported available renewable resources and plant characteristics in Table3-1 and Table3-3.

Table3-3 The characteristics of energy generation technologies in Chongming [10-14]

	Investment	Fuel cost	O&M costs(%	Efficiency	CO_2	Heat	Lifeti
Conventional	1134	0.044	2.0	34	687	-	30
Wind turbine	882	-	0.5	0.30	-	-	20
Solar PV	3044	-	0.2	0.12	-	-	20
Biomass	2273	0.090	3.5	0.30	18.81	56	20

The estimated annual generated electricity for PV, wind and conventional plant per kW capacity can reach 1100kWh, 2200kWh 4330kWh respectively, the operational time of biomass plant is considered same with conventional power plant. Fig.3-7 revels NPV indicators of each power plant within 20 years, wind plant presents the lowest construction cost and has the shortest payback period. However, due to the high installation investment, the PV plant can achieve benefit till the end of its lifespan, although it has the highest electricity feed-in tariffs. Compared with the conventional power plant, biomass plant shows advantage over GHG emission reduction. However, due to its relative low efficiency, high fuel and construction cost, the plant cannot achieve profit by selling electricity to the grid in recent electricity market. It may be favorable to run the biomass plant in combined heating and power (CHP) mode.

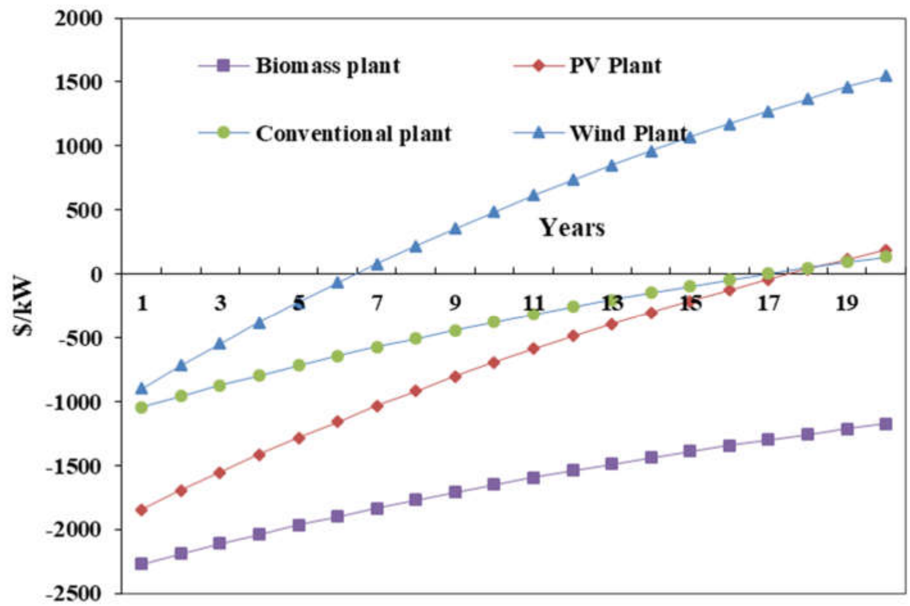

Fig.3-7. NPV of capacity individual plant in 20 years

For renewable energy resources, biomass power plant usually operates with constant power output, PV plant shows a better economic performance than biomass plant in longer run time. We suggest that it is better to choose the wind and solar PV as primary renewable resources to increase the electricity self-sufficiency in Chongming Country. Output of PV and wind usually features with daily and seasonal fluctuation. The power reliability will become a challenge for the public power grid when a large ratio of variable renewable energy resource is integrated. Considering the nature intermittency caused by installed PV and wind capacities, the least proportion from the lager-scale power production units should be not less than 40% to ensure the public grid security according to the public grid regulation in China. Currently wind plant accounts for the mainly contribution of variable renewable power resources (wind capacity 291MW, PV capacity 4.8 MW) in Chongming. Power generated from the PV usually has predictable accuracy and controlled advantage over wind power, renewable power plant based on combined renewable energy resources (PV, wind) has less excess power production than 100% of either individual renewable energy resource and improve the power utilization effective. Vary the combined proportions of PV and wind mainly through increasing PV participated ratio that ranges from 0.1 to 0.3, then analyze its economic performance among different scenarios considering the parameters of power generation technologies depicted in Table3-3. Fig.3-8 reports NPV of different combined proportions of renewable energy resource plant for Chongming district.

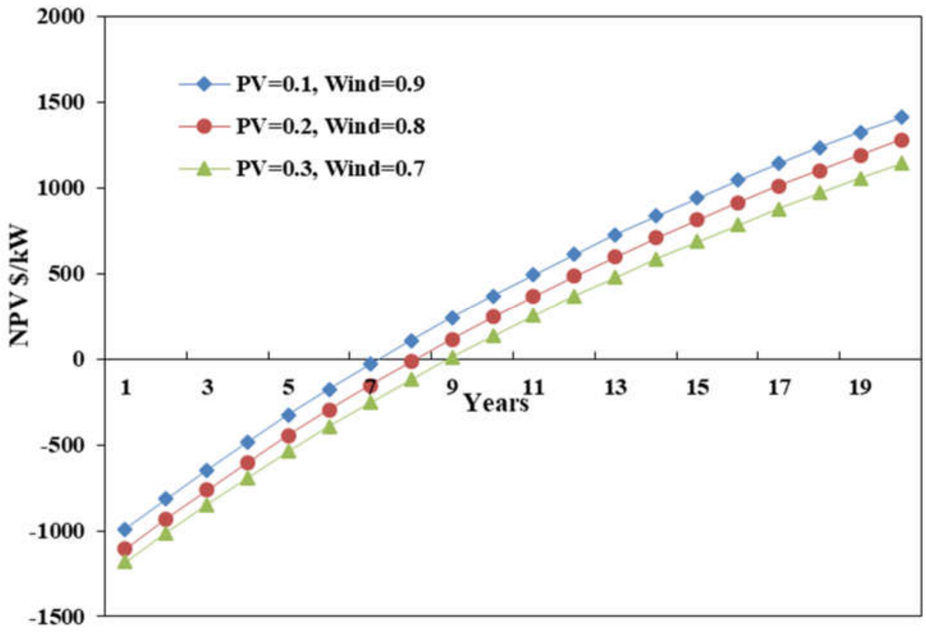

Fig.3-8. NPV of capital combined PV and wind turbine power plant

Fig.3-8 shows the economic performances of renewable power plants with different combined proportions of PV and wind resources. This installation of combined renewable resources will offer a promising solution to decrease the highly power imported dependency. In addition, a proper combined PV and wind resource power plant still shows a shorter payback period, it can also achieve great GHG emission reduction compared with the conventional power plant. Currently the government and enterprises jointly share the profits and risks of renewable energy development. However, the existing higher renewable electricity feed-in tariffs is not a sustainable development long operational time. The price decreasing in PV power plant initial investment will make this combined plant more economical acceptable and environmental attractive.

3.4.2 Demand side analysis

With the socioeconomic and urban development of Chongming Country, household and commercial electricity demand is rapidly growing. There is a great potential to reduce power consumption through energy efficiency efforts in household and tertiary buildings, such as update the high efficiency appliances and proper demand management strategies. In this research, all the analysis were carried out based on the expected electricity demand in 2020. In the following, we focuses on performance of power demand reduction by updating electrical saving technologies mainly including: lighting, air conditioner and refrigerator systems, based on the mainly identified electricity consumption parts in buildings classified in Table3-2. In order to evaluate the cost and energy saving benefits through forming the VPPs via aggregating updated advanced appliances in demand side, firstly we summarized the characteristic of the implemented electricity saving equipment and its unit investment in Table3-4, mainly investigated through website information and expert engineering experience.

Table3-4 The characteristics of implemented high efficiency equipment

Equipment	Electricity saving	Installed	Investment ($/kW)	Life span (year)
Lighting	1050	65310	300	3
Air conditioner	500	250668	350	10
Refrigeration	700	113036	900	15

In the practical project, the energy saving investment is most often of high concern. Thus, life cycle cost analysis is used to determine the economic performance of the selected three advanced technologies, the initial capacity cost and electricity saving were used to calculate the net present value (NPV_{app}) for each implemented appliance in Eq.3-5, the calculation including the interest rate i choosing 4%, n is 15 year calculated period for each equipment, j presents the generic year, R_{save} presents annual revenue from saved electricity per capacity, C_{app} is the initial capacity cost of the updated equipment. The calculated results in Fig.3-9 show that air conditioner presents the shortest payback period among advanced appliances.

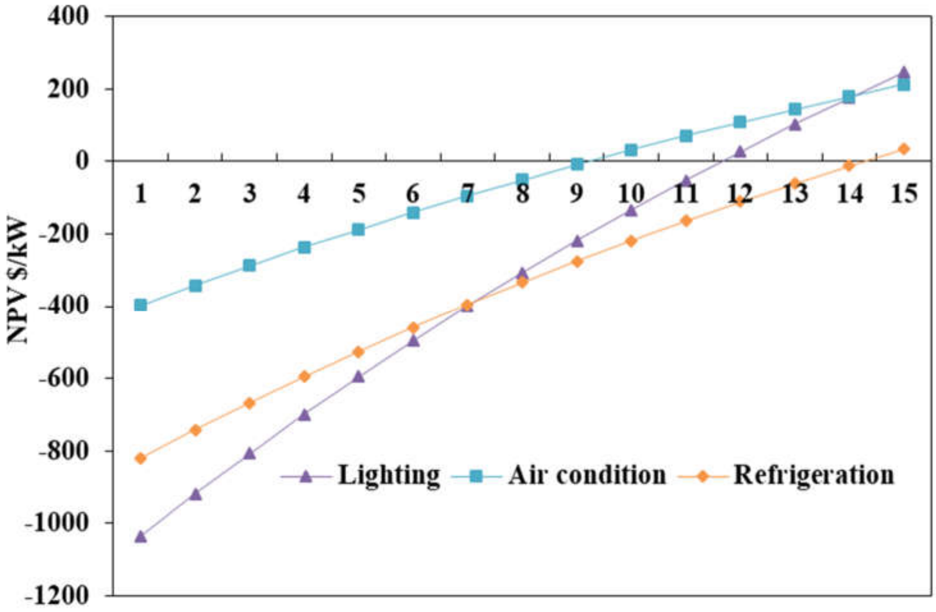

Fig.3-9. Net present value for different efficient appliances

$$NPV_{app} = \sum_{j=1}^{n} R_{save}(1+i)^{-j} - C_{app} \quad \text{Eq 3-5}$$

The annual electricity saving potential per average capacity of the VPPs in demand side, which can be seen as combined electricity saving ability from the implemented high efficiency equipment (lighting, air conditioner and refrigeration), that is 637 kWh per year at the capital cost of 680 $/kW. As shown in Fig.3-10, the join of the VPP can bring the electricity saving for the consumers and GHG emission reduction benefits to the society, replacing the expansion construction of conventional power plant to meet the increasing electricity demand. In China' electricity market, generated power is firstly sold to the electrical enterprises then delivered to the consumers through the public grid, the feed-in and sold electricity price are usually govern by the local government. Therefore, the outcome influence of the VPP may be attributed to both consumer and the power supplier, such as the implement of high efficiency appliance needs a high initial investment, power plant will supply less electricity to the society, which will influence its electricity sold income in long run. Therefore, based on the electricity market, a proper payment mechanism art between power and demand sides is essential to encourage the form of the VPPs in Fig.3-10. In order to analyze the economic profit balance properly and develop commercial incentive agreement between both demand and plant sides, following part analyzed the performances of built electricity market model in different scenarios via changing the feed-in tariffs for plant side and corresponding electricity fee for demand side.

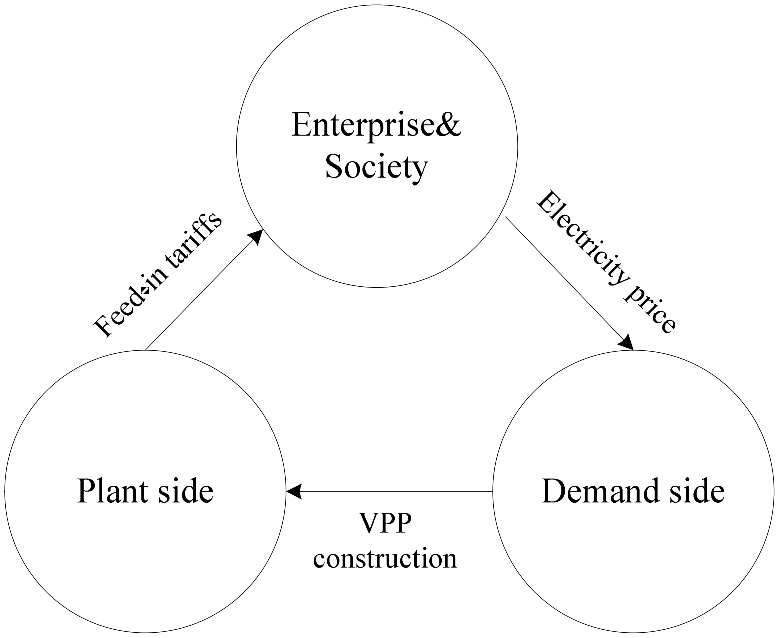

Fig.3-10. The concept and structure of VPP

3.5 Market innovation

As shown in Fig.3-11, the payback period of the updated equipment in building will become shorter with the increasing electricity tariffs. Therefore, in order to analyze the economic performance of the VPP in demand side, Set the current market 0.12$/kWh electricity fee as the baseline to calculate the total annual cost. After the application of high efficiency appliances, the electricity demand reduction can be achieved, the total electricity fee for demand side will not overpass baseline when the electricity fee is below 0.16$/kWh as presented in Fig.3-12. Obviously, an optimal increase of electricity tariffs can help short the payback period of the VPP and encourage the consumers to update the high efficiency appliances in buildings.

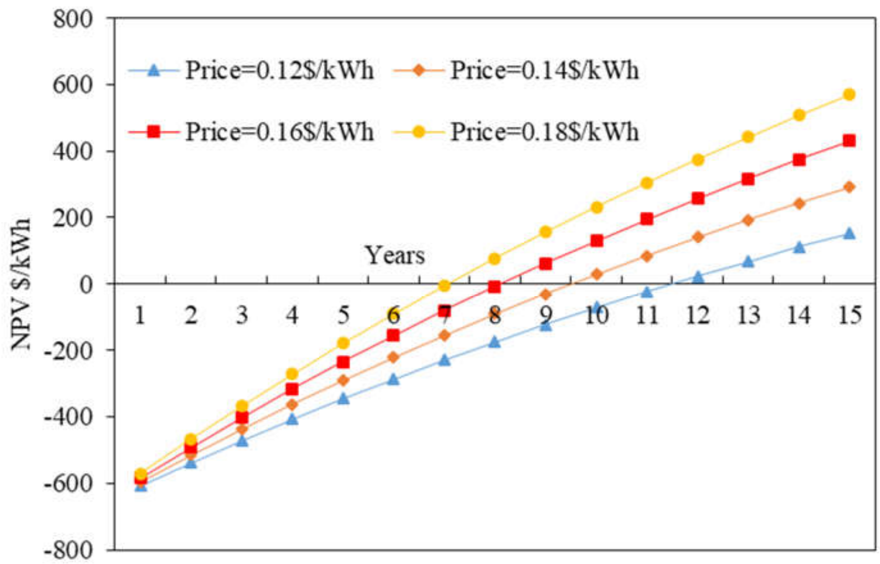

Fig.3-11. Net present value of demand side in VPPs under different electricity tariffs

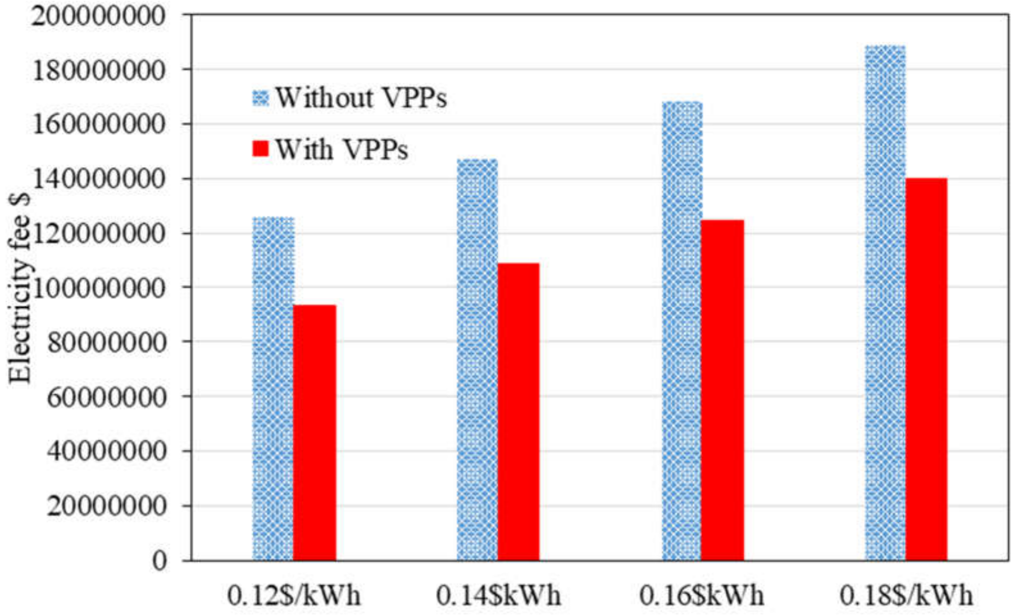

Fig.3-12. Electricity fee of demand side in VPPs under different electricity tariffs

However, after the form of VPPs in demand side, the power delivered from the plant side will decrease, in order to analyze its influence on conventional power plant's profits, set the income baseline includes: total electricity supply 3200GWH/year, 273 GWH/year produced from VPPs calculated in Section 3.3.2, feed-in tariffs 0.066$/kWh and fuel cost of 0.044$/kWh for the main type of plant based on raw coal. The profit variations in plant side were carried out according to different feed-in electricity tariffs depicted in Table3-5, Scenario1 presents the current condition of electricity market in Chongming. Considering the operational and management cost, the increasing rate of electricity price is 0.01$/kWh higher than feed-in tariff among scenarios. Fig.3-13 shows that the annual revenue of sold electricity will reduce 6006000$ per year after updating of high efficiency appliances under the current electricity market. However, the plant side will soon achieve an income growth by rising the feed-in tariffs to 0.076$/kWh.

$$\begin{aligned} Profit_{increase} &= \left[\sum_{j=1}^{n} profit_j (1+i)^{-j} \right] - C_{cap} \\ &= \left[\sum_{j=1}^{n} (price_{VPP} \times power_{VPP} - Income_{baseline}) \times (1+i)^{-j} \right] - C_{cap} \end{aligned} \quad \text{Eq.3-6}$$

Table 3-5 Plant feed-in tariffs and demand electricity price for each scenario

	Scenario1	Scenario2	Scenario3	Scenario4
Feed-in tariffs ($/kWh)	0.066	0.076	0.086	0.096
Electricity prices ($/kWh)	0.12	0.14	0.16	0.18

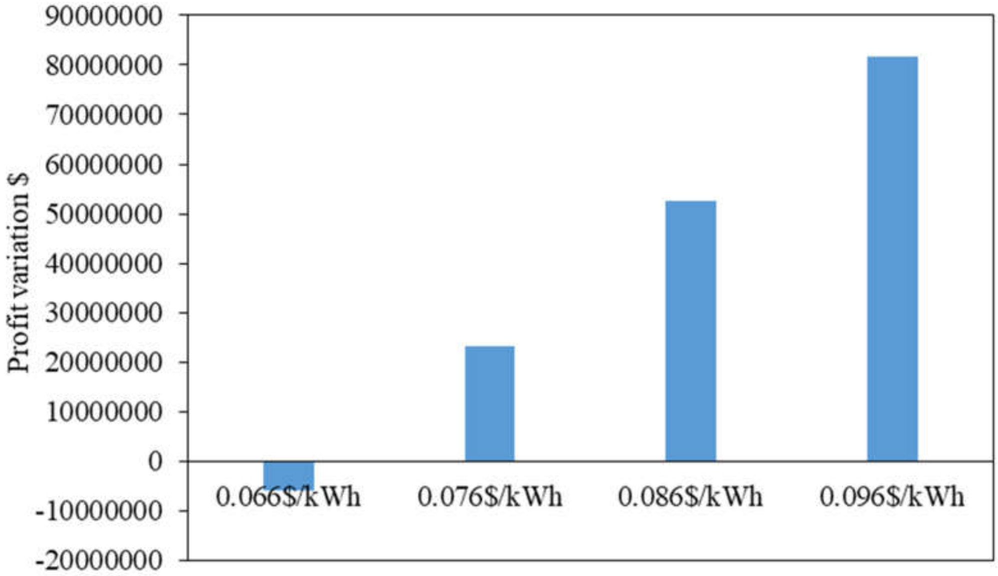

Fig.3-13. Annual profit variations of power plant side under different feed-in electricity tariffs

The formation of VPPs takes place of the construction of new power plant, which can save a large initial capacity investment. However, there also exists a power generation reduction from plant side, which will influence its revenues from the sold electricity. The plant side may need to rise the feed-in tariffs to balance its income in long term run. The economic performance has been evaluated by the increase profits in plant side under different electricity feed-in tariff scenarios according to Eq.(6). Where i is the discount rate, choosing 0.04, n is lifetime of the VPPs, $price_{VPP}$ is feed-in tariffs, $Power_{VPP}$ is the annual electricity saving amount from VPPs, $Income_{baseline}$ is the income by selling equivalent saved electricity to the public grid under current electricity market, the C_{cap} presents the replaced construction capital of the new conventional power plant. Fig.4-14 shows the profits will always be a positive value in 15 years perspective, if the feed-in electricity price is not below 0.066$/kWh. The red dot line presents the construction investment of the VPPs through combining updated lighting, air conditioner and refrigerator systems in demand side, the economic benefit brought to plant can overpass the cost of high efficiency appliances implemented in buildings within 12, 5 and 3 years corresponding the electricity feed-in price 0.076$/kWh, 0.086$/kWh and 0.096$/kWh respectively.

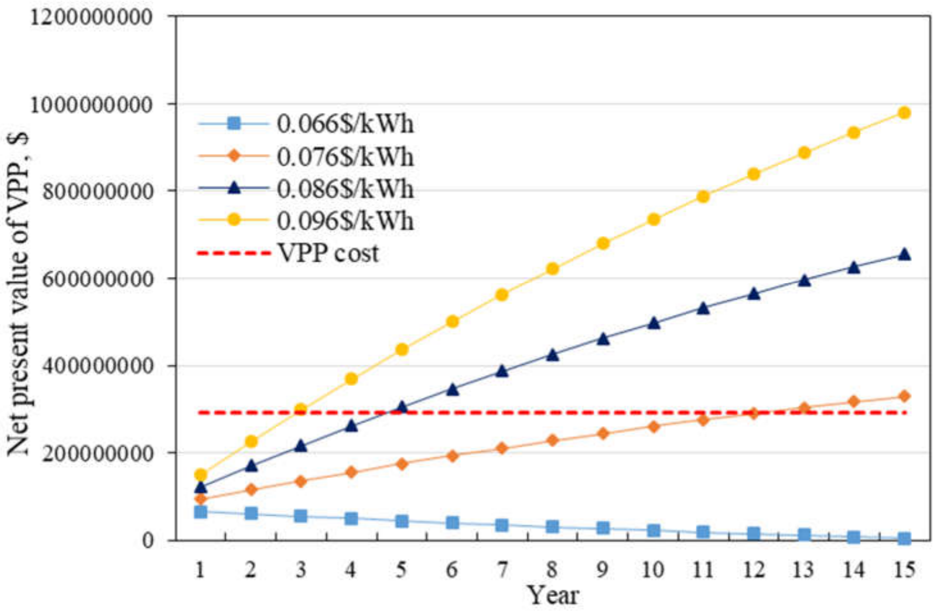

Fig.3-14. NPV of power plant side under different electricity feed-in tariffs

Due to the high initial investment, the government may need to implement proper incentive policies for the update of high efficiency appliances in demand side. The completion of VPPs can replace the role of constructing new power plant, which can bring a direct capitalized cost saving. Moreover, it also makes contribution to the GHG emission reduction in the society in long run. Therefore, an optimal energy market structure could encourage participations of power supplier and customers should be considered, in the following section, analyzed performances of VPPs under different scenarios described in Table3-5 including: economical profits, payback period of VPP. Then suggesting using different revenue ratios (0~0.4) in plant side as incentive fund to finance the update of advanced appliances in demand side, and finally analyzed the capacity investment cost variations of VPP per capacity for demand customers. Return profit ratio is defined as value ratio of incentive fun payed for demand customers to increased revenue of power plant. As shown in Fig.3-15, after the optimal adjustment of the feed-in tariffs and electricity price, an optimal return from the increased income of the plant side can reduce the capacity investment of the VPP effectively. Part of plant revenue used as incentive fund for demand customers, encouraging the update of advanced appliances. Results indicate that the capacity cost of the virtual power plant ranges from 680$/kW~68$/kW when return profit ratio increase from 0 to 0.4 in Scenario3.

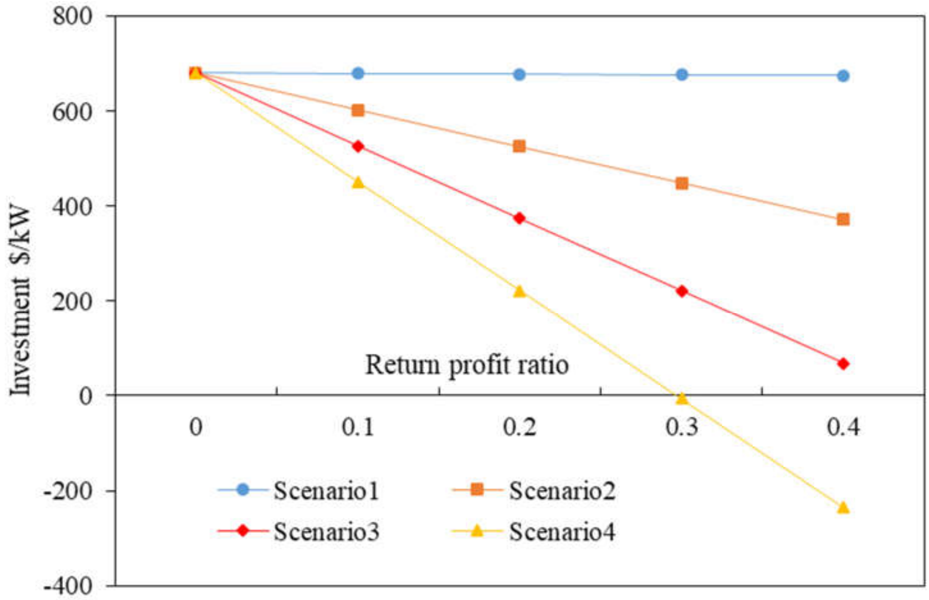

Fig.3-15. The investment cost variations of VPP in demand side after subsidies

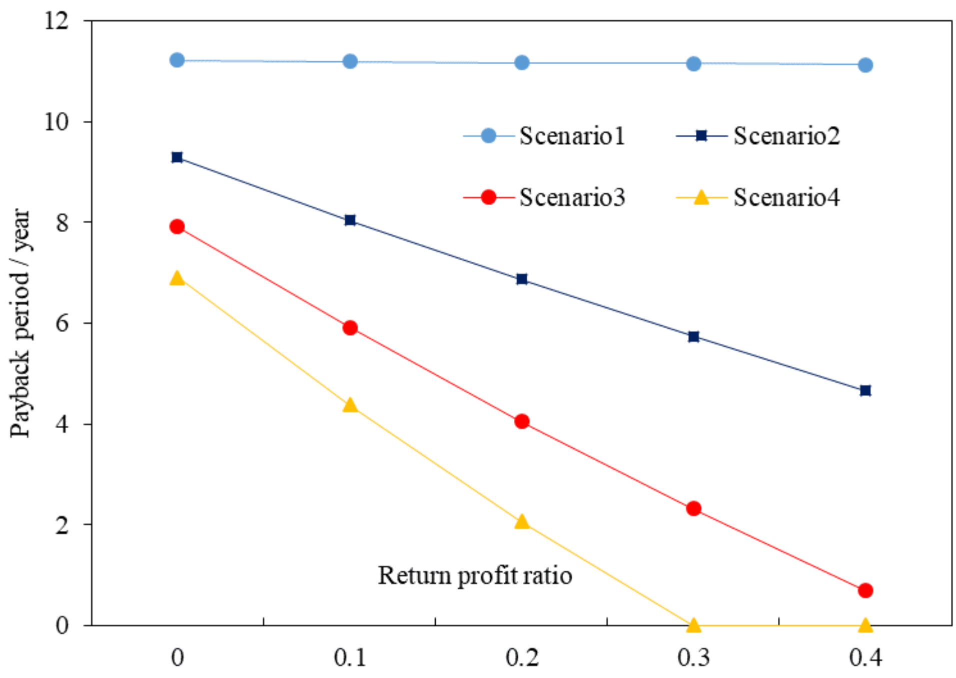

Fig.3-16. The payback periods of VPP under different return profit ratio from plant side

According to the proposed electricity market and incentive mechanism, the payback periods of VPP formed in demand side were carried out in detail under different scenarios, Fig.3-16 depicts the detail variations. Cash flow delivered from the plant side to the demand side should be considered, it can help short the payback period value of the VPP and provide increase profit for the power producers. For example, in scenarios3 (0.086$/kWh feed-in tariffs and 0.16$/kWh electricity price) when the return ratio of plant revenue varied from 0.0~0.4, the payback period of the VPP can sharply reduce from 7.9 years to 0.96 years. Moreover, the annual total electricity fee for the user will not overpass the cost before the implementation of VPPs depicted in Fig.3-12.

3.6 Summary

This chapter proposed the concept of the virtual power plants (VPPs) to increase the local power self-support and reduce the total electricity demand in the islands. The economic performance of renewable energy resources and utilization potential were analyzed based on NPV indictor and lifecycle cost analysis, optimal combination of wind and PV plant is a favorable option due to its shorter payback period compared with conventional power plant. However, the existing high feed-in tariffs policy for renewable power generations is not sustainable development for the future power supply framework. The price decreasing in renewable power units may make this plant more economical acceptable and environmental attractive in future.

Analysis result found that implement high efficiency appliances (advanced lighting, air conditioner and refrigerator) has a promising potential to reduce the electricity in household and tertiary industry. The VPPs can not only save the construction cost of new power plant, but will also reduce the GHG emission. However, VPPs also cut the total power supply from the plant sides, which may influence the plant's profits in long run. In addition, it needs a high investment cost of high efficiency equipment in building. Therefore, sustainable financing strategies is important for the sustainable and stable development of VPPs. The energy market structure is changing due to the application of the VPPs, aiming at benefitting power plant industry and incentive users' participation in demand sides. Analysis shows that an optimal increase fee in both feed-in electricity tariffs and electricity price sold to demand side is an effective way to implement the VPPs. Results show that the return on the power plant increase profits will make a contribution to shorting the payback period of VPPs for the consumers efficiently. This VPPs considered can provide economic and environmental benefits to both plant and demand sides with a developed incentive payment mechanism. The proposed VPPs concept and its performances carried out in this research can be important references for the local policy maker to build a sustainable power supply framework and reduce carbon emissions.

This chapter mainly does a feasibility analysis of power supply-demand management, considering both supply and demand side, results verify the effectiveness of VPP concept based on cooperation between supplier and customer. In the following chapters, with increasing renewable penetration, the challenges and chances of large renewable integration will be identified, such as real-time renewable integration, power flow dispatch. And the performances of high efficiency appliance or power technologies in demand side will be investigated in detail.

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Chapter 4

ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN PLANT SIDE

CHAPTER FOUR: ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN PLANT SIDE

4.1 Introduction

This chapter will investigate the impacts of increasing share of variable renewable power generation (PV) and examine the role of large-scale pump hydro storage dispatch. This chapter uses the yearly history load data and power production of Kyushu region for analysis, collected data is composed of hourly load and generations during 2017. Hourly productions by nuclear, thermal plants, hydro, PV and wind are provided, respectively.

4.1.1 Objective location

Fig.4-1 presents the locational scenario of the examined objective in this section. Kyushu island lays off the south end of Honshu, as Japan's third largest island population reached 13 million by the end of 2016, covers 42231 km^2, 11.2% of national land area. Kyushu Electric Power sales shared 9.2% of nationwide electricity business, according to Kyuden annual report 2017. Kyuden constructed power supply system through an optimal mix plan of power sources from the perspective of securing long-term sustainable development, such as promoting safety and security of nuclear power, actively integrating local renewable energy resources.

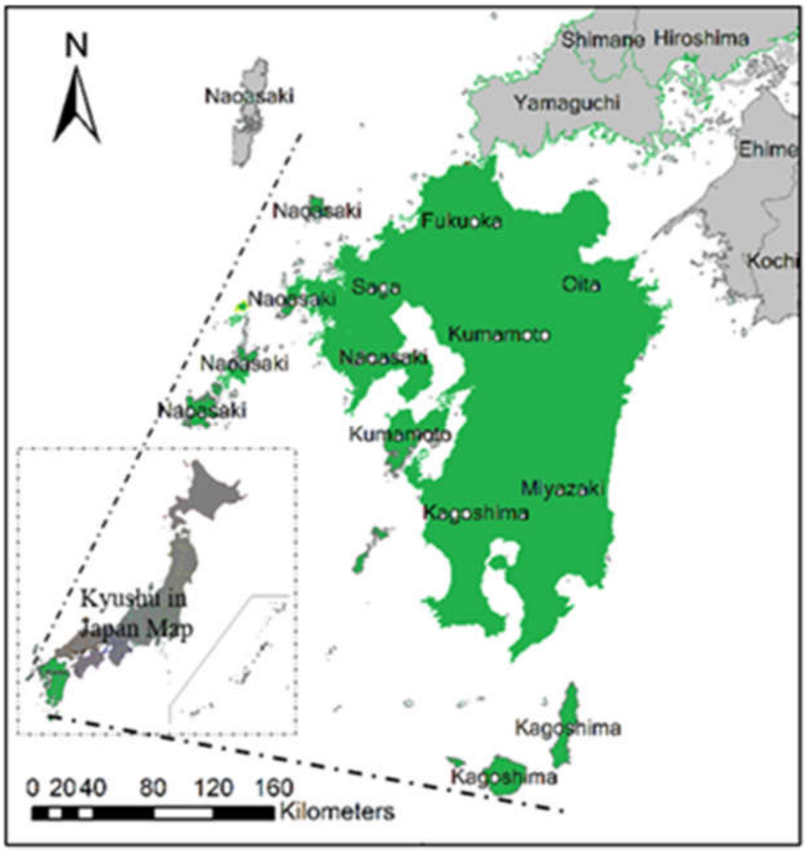


Fig.4-1. Location scenario of Kyushu Island

4.1.2 Data resource

There are increasing infeed renewable energy in Kyushu region. As the main renewable power resources, development of solar PV has been characterized by considerable growth rate over recent years. This development is mainly driven by the guaranteed feed-in tariff which has been launched since 2012. Integrated PV capacity experienced sharp increases, cumulative amount increases from 0.33 GW in 2008 to 7.87 GW by 2018.02 as shown in Fig.4-2.

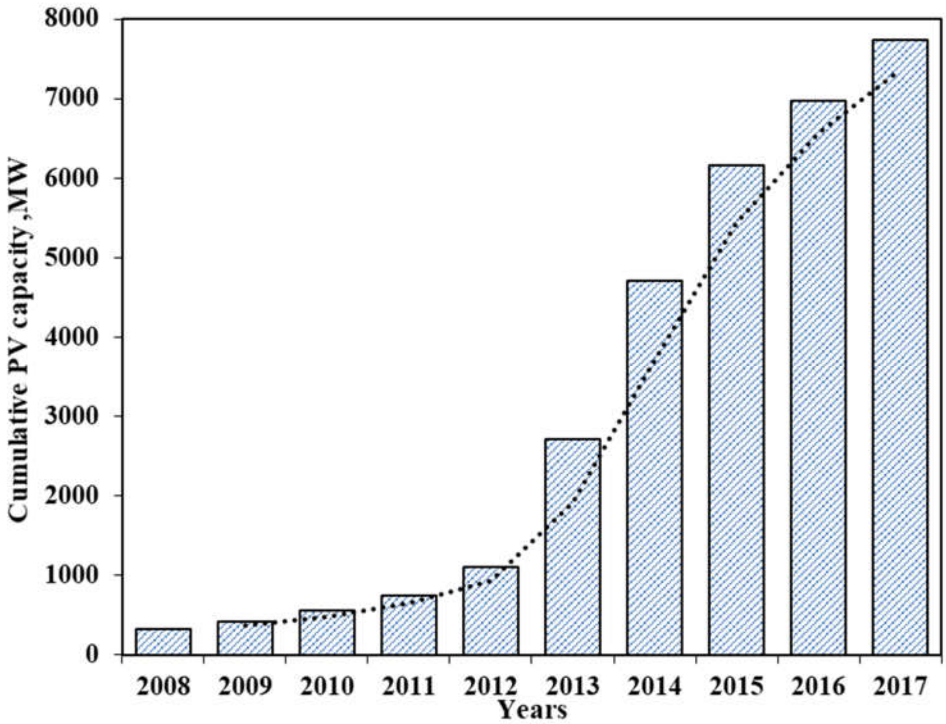


Fig.4-2. Cumulative integrated PV capacity in Kyushu Island

As the largest available renewable resources, cumulative integrated PV capacity presents the largest ratio of total power generating capacity, which has reached 26% of total power capacity in Kyushu. Next is LNG, nuclear and coal based plants respectively, illustrated in Fig.4-3. It should be noted that 2800MW capacity of nuclear plant still remains shut down since 2012 Fukushima Crisis, considering the power safety and reliability. Current power contribution by sources is presented in Fig.4-4, base load power plants are nuclear, geothermal and biomass that are set to operate the entire year with constant output. Hard coal and combined cycle gas turbine are considered as medium load power plant, which have lower starting and shut down times and show more flexibility. Peak load power plants refer to gas turbine and oil based power plant that are operated to meet the highest demands on daily basis. PV as the largest renewable resource, which accounts for around 10% of total power generation in 2017. Capacity factor of thermal generators will decline through large scale variable renewable energy integration, even reach their flexibility limitation. Table 4-1 illustrates the flexible characteristics of the main thermal generators.

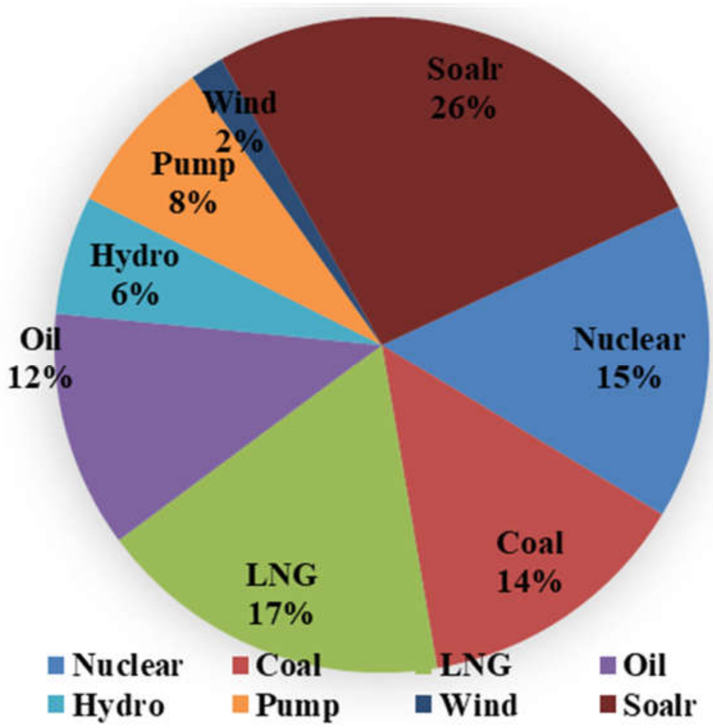


Fig.4-3. Power capacity structure of Kyushu power system

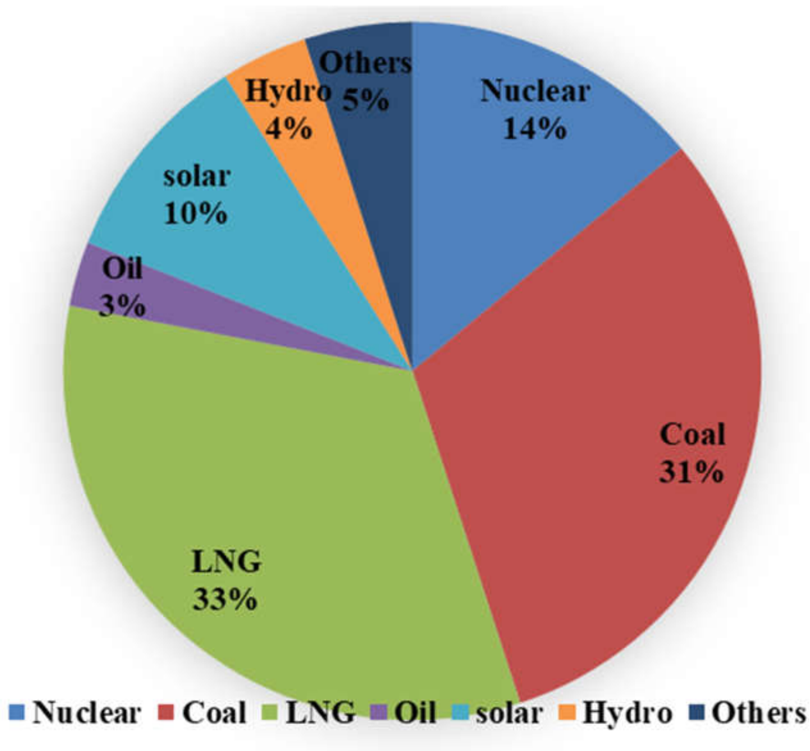


Fig.4-4. Power contribution ratio by power sources in Kyushu

Table 4-1 Flexible characteristics of main thermal generators

Type	Nuclear	Coal	LNGCC	LNG ST	Oil	Biomass
Maximum increase rate of	0	0.31	0.75	0.75	1	0.31
Maximum decrease rate of	0	0.58	0.484	0.396	1	0.58
Minimum output level	0.3	0.3	0.2	0.2	0.3	0.3
Efficiency	1	0.418	0.484	0.396	0.394	0.2
Lifetime	40	40	40	40	40	40
Share of daily start and stop	0	0	0.5	0.3	0.7	0

LNGCC: LNG combined cycle, LNG ST: LNG single turbine

4.1.3 Load and generation scenarios

Fig.4-5 shows the layout of the power system structure and a typical daily (4th May, 2016) supply/demand balancing scenario of Kyushu, aggregated PV generation plays a dominant role in power supply during daytime, which contributes to largest daily variabilities compared with other renewable resources. Geothermal and nuclear generators generally run with constant output throughout the day, thermal generators (natural gas, coal and oil) as the flexible generators will adjust their output generally range from 0.3 to 1.0 ratio of peak capacity, to meet the changes of renewable output and consumption variations.

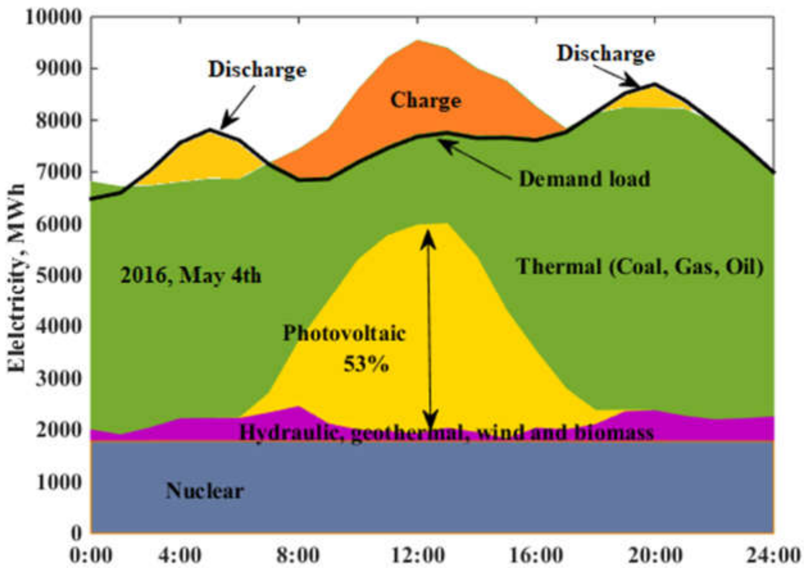


Fig.4-5. Structure layout of the power supply and demand system in Kyushu

Aggregated integrated PV contributes to largest daily variabilities compared with other renewable resources. Geothermal and nuclear generators generally run with constant output, thermal generators (natural gas, coal and oil) as the flexible generators will adjust their output to meet the changes of renewable output and consumption variations. Higher daily PV penetration level may greatly mitigate the peak demand and the shape of load curve with evening peak and afternoon bottom, occasionally referred to as 'duck curve'. In September 2014, Kyushu Electric Power even declared the temporal stop of RES integration for the concern that PV output could excess the lower demand during transition season. In addition, extension of PV also raises challenges to the power control and management due to its intermittent nature. Pumped hydro station is used to absorb surplus VRE generation (typically PV production) during daytime and releasing the stored energy for peak shave, improve the capacity factor of thermal generators on daily basis. As the main large-scale grid energy storage systems, the total capacity of pump hydro storage in Kyushu has reached 2600 MW by 2017, mainly pump hydro storage systems are shown in Fig.4-6.

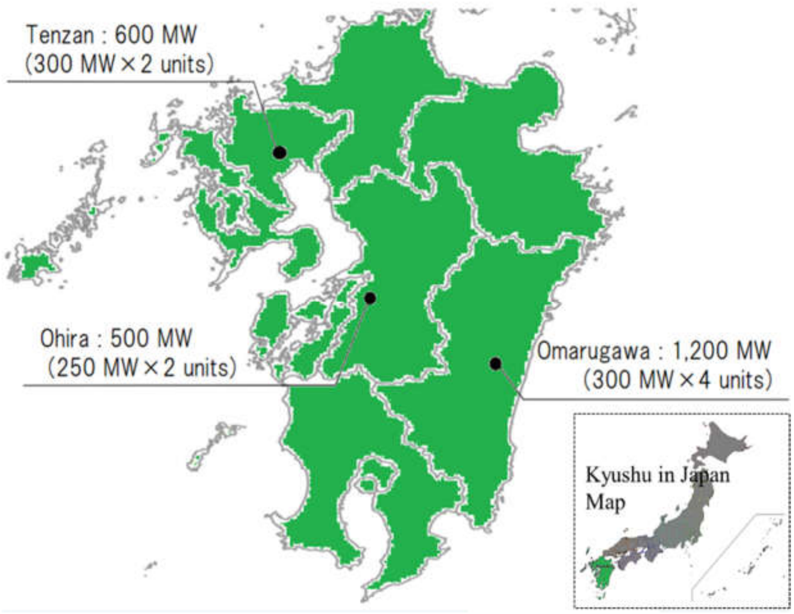


Fig.4-6. Location of main pumped hydro storage system in Kyushu

Fig.4-7 & 4-8 present the distributions of yearly electricity load and PV production of Kyushu in color scale, original data was collected from 2016.04-2017.03 at hourly interval. Electricity demand is as a function of time of day and seasonal periods, there are considerable variations in both daily electricity consumptions and patterns across the year. Home and working activities, such as electric heat, lighting and air condition usages lead to the early morning and night peaks in winter. Peak period shifts towards midday in summer, which is mainly driven by the extensive air cooling utilization, the peak value can be almost twice as big as the level of valley value. The daily load profiles are relatively flattened in mid-seasons and change less compared with winter and summer periods. As PV contribution concentrates during midday time as described in Fig.4-8, it shows highly generating capacity in summer and mid-seasons, it can also confirm that the PV production could greatly shape the net grid load during mid-season days, the PV production coincides with the daily peak load driven by the air conditioning load in summer period, thus may enhances the peak capacity credit.

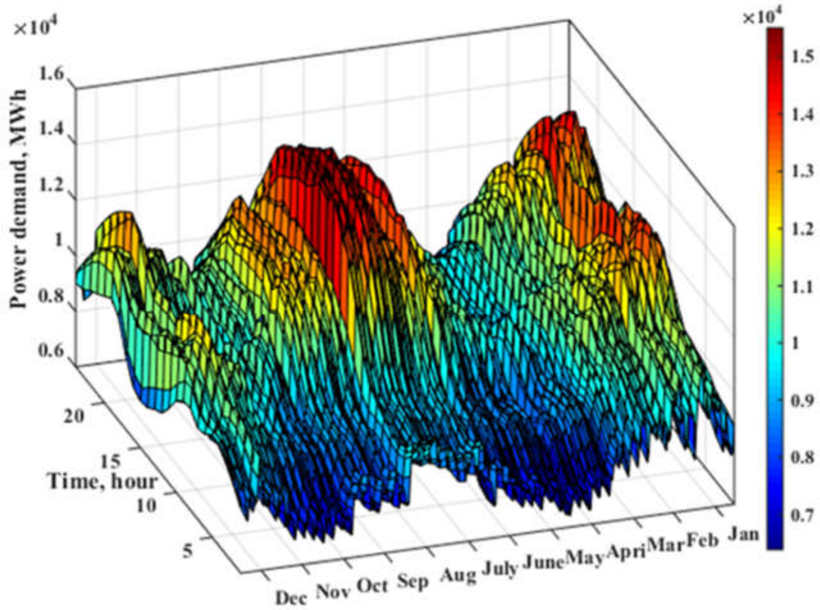


Fig.4-7. Color scale distributions of electricity demand in Kyushu

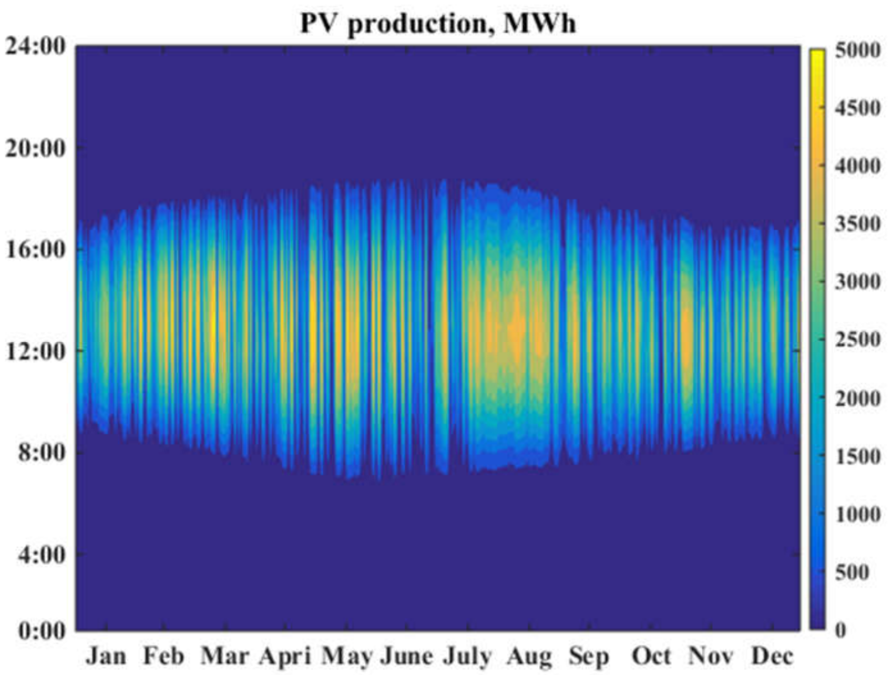


Fig.4-8. Color scale distributions of solar PV production in Kyushu

Considering supply demand balance, capacity constraint, load following constraints, pump hydro storage systems are implemented for enhancing regional grid flexibility and renewables exploitation. As shown in Fig.4-9, the pump hydro storage is mainly used to charge surplus PV generation during daytimes of mid-season and winter, bottom up the early morning valley to enhance thermal generator utilization in summer. The high air cooling load during hot days provides a good chance to absorb the great PV generations. The storage will be released for night peak shave, as a result enhance the daily grid flexibility. Maximum charging/discharging capacities of pumped hydro station is 2479 MWh and 1645 MWh respectively, largest stored capacity reaches 15820 MWh, yearly total pump consumption 1306741 MWh and 887386 MWh discharge amount to 67.9% annual overall cycle efficiency.

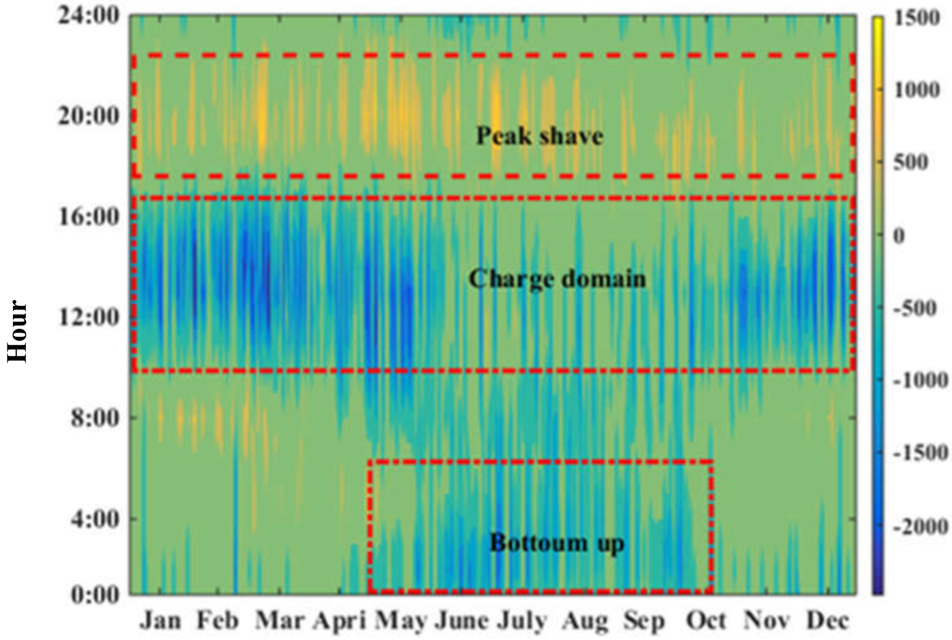


Fig.4-9. Color scale distribution of pumped hydro station

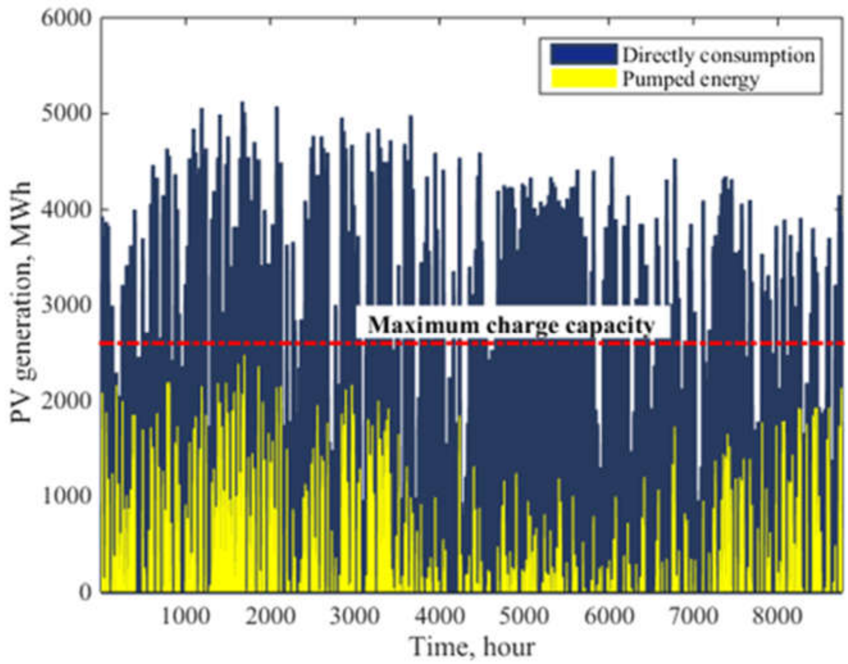


Fig.4-10 Hourly pumped solar energy and directly PV consumption

Fig.4-10 presents the distributions of hourly direct PV consumption and pumped PV generation, the maximum pumped scenario mainly distributed in spring and winter seasons. Pumped energy has not reached the maximum pump capacity (2600 MW). The summer solar generation profile can match the peak demand and present a high directly consumption, a large amount of PV generation could be directly absorbed by the grid driven mainly by air conditioning demand.

4.2 Approach

4.2.1 Grid load and PV integration

Fig.4-11 describes the daily average grid load and PV production profiles of Kyushu public grid in each month over a yearly period. It can clearly see that weather conditions have great influences on both demand load and PV production profiles. Generation of PV plant shows great intermittent over months, it experiences the maximum generating ability during summer period, output decreases in June due to the continuous rainy days, effective generating period is shorten in winter. It can clearly see that load changes in the technology mix of power consuming process and appliances. During mid-season, daily load is low and shows a relative flatten curve. Higher daily variations mainly occur in summer and winter seasons due to the rise of air conditioning loads. As PV contribution concentrates during midday time, it can also confirm that the PV production could greatly shape the net grid load during winter and mid-season days.

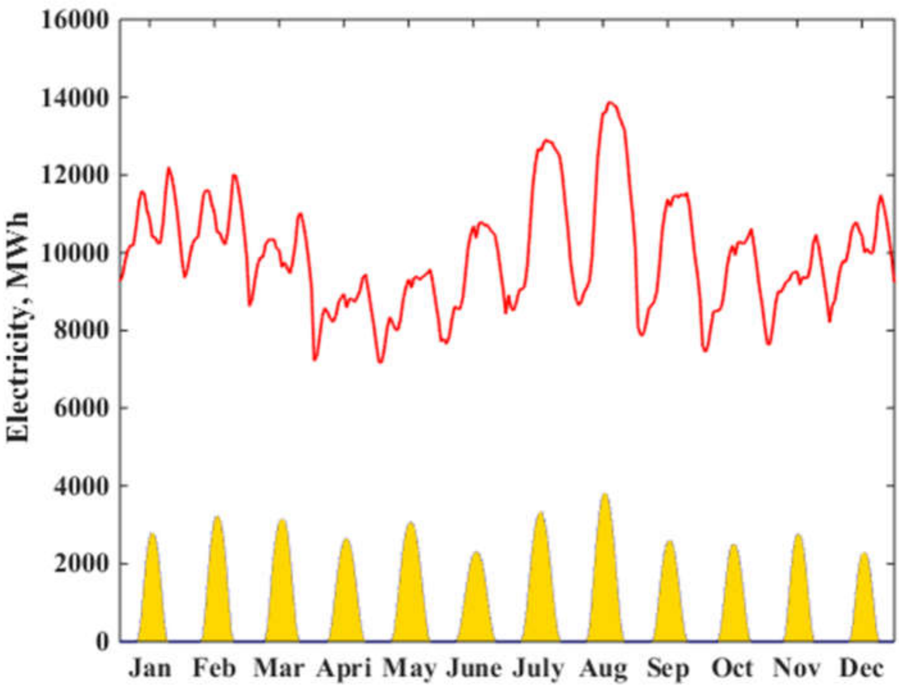


Fig.4-11. Daily average load and PV production of months in Kyushu

Fig.4-12 illustrates the temperature sensitivity of peak load in Kyushu region. History load and temperature are collected at 14::00 and 20:00, generally present the peak period for summer and winter. It can confirm that the slope of the data on the left side of Fig.4-12, for the temperature below 15 ºC, leading rise in heating demand. On right side, load increases when the temperature is over 25 ºC. and the peak loads driven by the massive cooling demand reaches around 16000 MWh as much as the 2 times of valley load. Compared with winter scenario, peak load increases at higher rate in summer for a given temperature difference. We cannot ignore that it may lead underestimated variations in daily demand curve by averaging time series over a day of month. Daily load in winter generally experience two periods in morning and night, which has a close relationship with activity based load consumption.

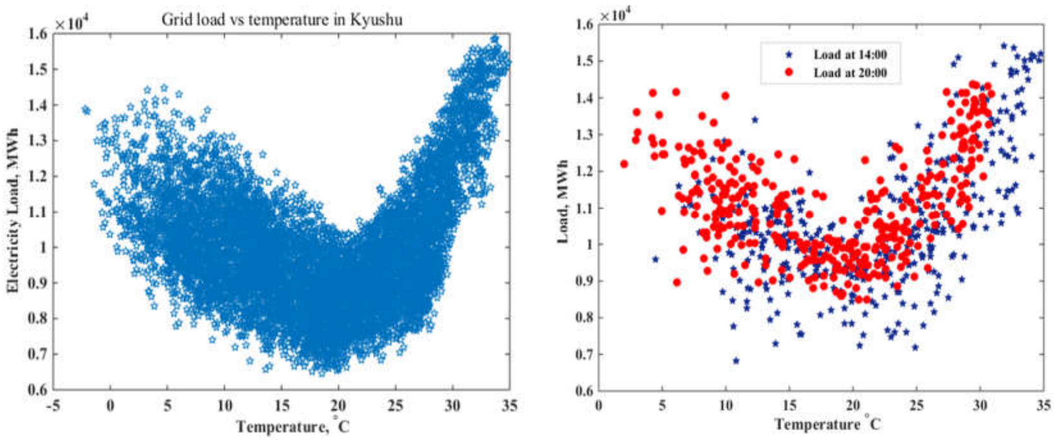


Fig.4-12. The temperature sensitivity of peak load in Kyushu

Hourly demand shows greater variations during the summer and winter seasons, and thermal generators may reach their minimum output due to the large PV integration and relative low demand load in April and May. Load leveling and peak load shifting has become important emissions for the grid utilities with concerns of power balancing security and quality maintenance, especially with high variable renewable penetration.

4.2.2 Load duration curve

Electricity demand is as a function of time of day, weather, season, aggregated diverse customers. There is considerable variations in both total electricity consumptions and patterns across the days. The summer time profile has one peak, driven mainly by air conditioning demand, PV system shows maximum generation ability during summer that provides the promising grid peak reduction as shown in Fig.4-11. There are two peak in winter mainly driven by evening lighting and electric heating, the solar peak at noon does not exactly match the load peak that occurs later in the early morning or evening. As PV penetration rises, the number of hours that net load may be lower than the limit of grid flexibility.

Effective load carrying capability of PV may be graphically visualized on annual load duration curve plot. The example presented in Fig.4-13, the effective capacity of PV is measured by its ability to reduce peak loading from load duration curve (blue line) to residual load duration curve (black dash dot line) without PV (5). Fig.4-14 illustrates the variations of PV peak credit capacity as a nonlinear function of PV production to grid load ratio. Initially, increased PV integration can effectively mitigate the peak grid load. Without storage dispatch, the increased rate of PV peak credit capacity becomes less with increasing PV integration, PV peak reduction ratio becomes saturated 8.0% after PV generation to load ratio is over 10%. Therefore, the uptake of storage dispatch is expected to play a crucial role in minimizing curtailment, enhancing PV effective utilization and grid load leveling, as a result offset solar power intermittence and inherent intermittent nature.

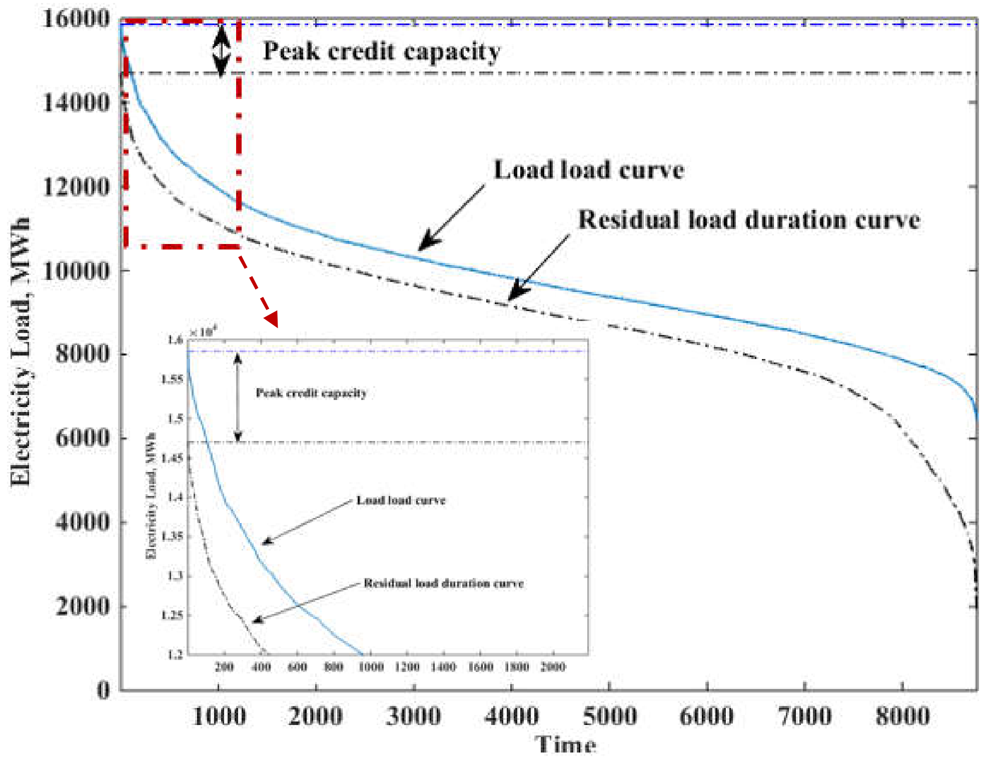


Fig.4-13. Peak credit capacity of PV at PV production to grid load ratio is 9.76%

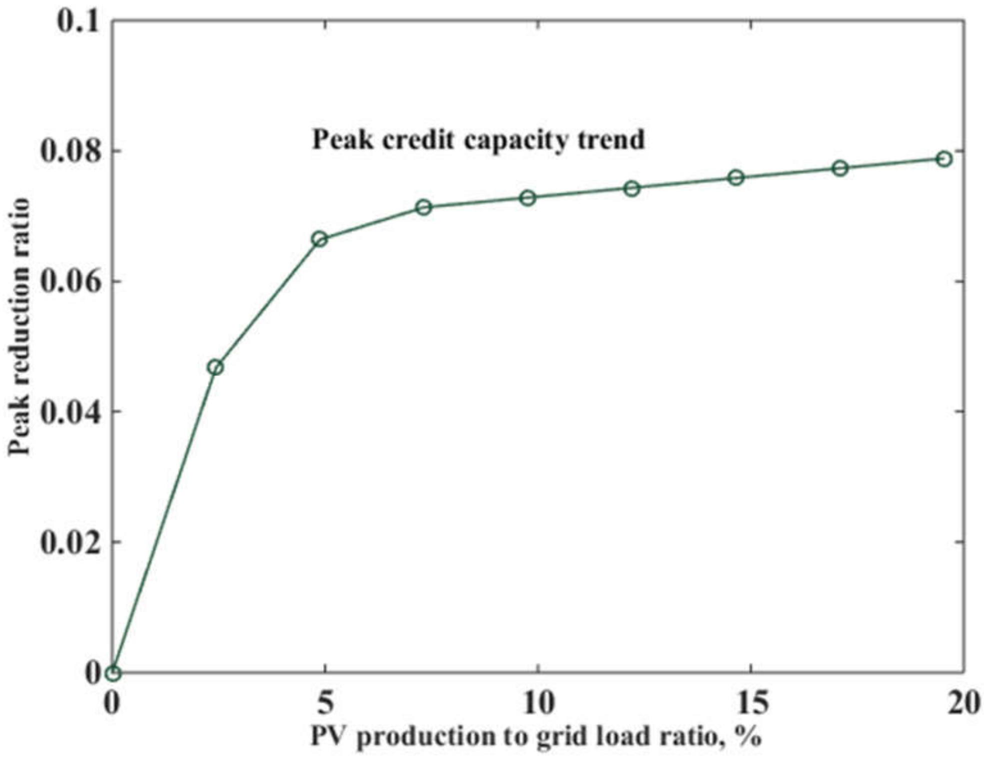


Fig.4-14. Peak reduction ratio as function of PV production to grid load ratio

The ability of grid to accommodate VRE has a close relationship with the shape of load curve, which highly determines the reliable operation to maintain a dynamic balance between electricity generation and consumption. The grid flexibility is defined as the portion of the annual peak capacity wherein power can be ramped up and down without needing to turn off any base-load power plants, it presents the capability of the power system to maintain reliability under VRE uncertainty. The impacts of changes on utilization of dis-patchable plants, capacity credit and overproduction are usually assessed according to RLDC. The flexibility highly depends on the mix of its generators and largely constrained by the inflexible generators (nuclear, base-load plant). As shown in Fig.4-15, the sorted residual load curve (normalized to peak value) of Kyushu was obtained by subtracting hourly simultaneous PV generations. PV shows relatively low peak capacity and largely decreases the based load, it has resulted the grid flexible limitation when PV production to annual load ratio is over 10%. It is also worth to note that the RLDC does not capture ramping and cycling requirements, since that would require the chronological order of the residual load, net load fluctuation from hour to hour will be lost in a duration curve. PV production will dramatically decrease the production from medium flexible plants, even reach the grid limitation that exceed the constant output from nuclear and base-load thermal plants that set as 0.35 ratio of maximum yearly grid load.

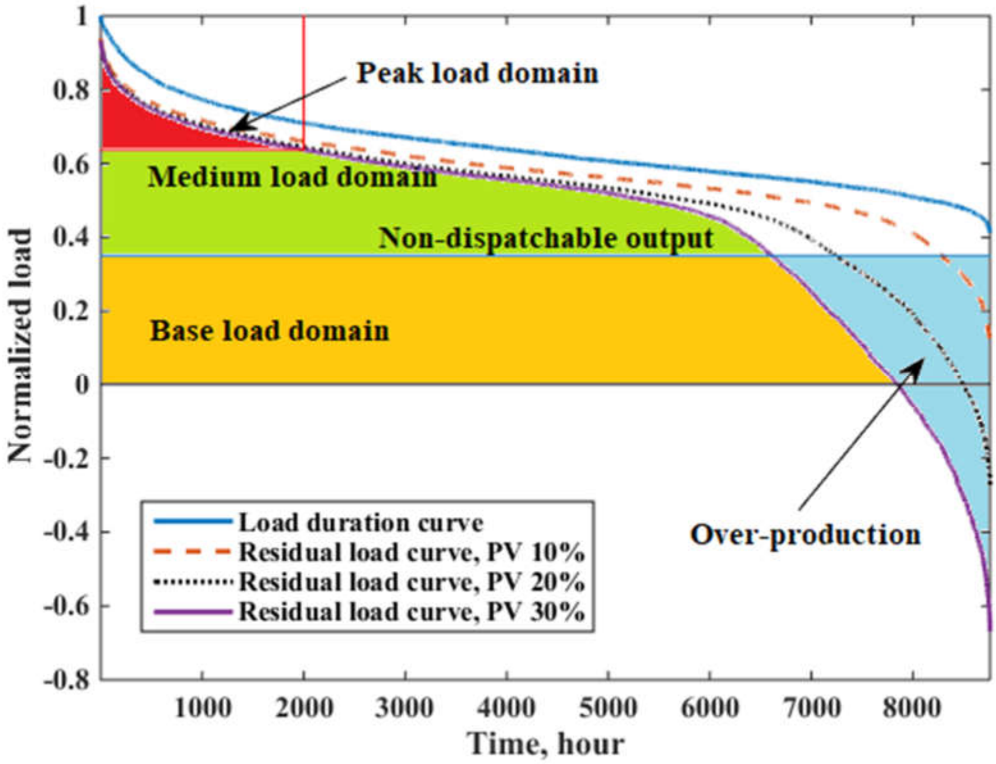


Fig.4-15. Residual load duration curves for different integrated PV capacities based on hourly Kyushu grid load and real PV production during 2016.04~2017.03

4.2.3 Simulation model

As PV capacity increases, pump hydro storage systems are implemented for enhancing performances of regional grid flexibility and PV integration. Pump hydro storage as main established technology for large-scale electricity storage is used to charge surplus PV generation considering grid flexibility limitation, stored energy will be released for shaving residual peak load, as a result enhance the daily grid flexibility. As a result, pump hydro storage reduces the lost variable production and increases the integration rate of intermittent renewable energy. The storage system generally is characterized by three main indicators: charging power, discharging power and energy storage capacity. Storage system should operate within its nominal cycle range. Parameters used in the simulation model is described in Table 4-2.

Table 4-2 Technical parameters of the power supply system

Variable	Value
PHS output, Max. to peak load ratio	0.15
Depth of discharge, %	80 (15%-95%)
PHS reservoir (maximum kWh to kW ratio)	7.0
Pump capacity (to reservoir ratio)	0.20
Discharge capacity (to reservoir ratio)	0.18
Pump efficiency, %	85
Discharge efficiency, %	85
Flexible plant output range	0.3~1.0
Constant output in grid	0.35

The pump/discharge capacities of the pump hydro storage are limited to maximum pump/discharge rates to the storage reservoir capacity (20%, 18% of upper reservoir for pump and discharge respectively), the potential energy stored in the upper reservoir is limited to maximum operation period (7 hours) with nominal output. Daily depth of charge state ranges from 15%~95%, we introduce the cycle efficiency to present the conversion loss of pumping and discharging process. Detail technical parameters are illustrated in Table 4-2.

The daily demand and supply balance is constraint as follow:

$$P^{i}_{constant} + P^{i}_{fle} + P^{i}_{PHS} + P^{i}_{PV} = demand^{i}_{grid} \quad \text{Eq 4-1}$$

Where, $P_{constant}$, P_{fle} stand for output from non-dispatchable base-load plants and flexible plants, respectively. P_{PHS} presents power flows from pump hydro storage, positive value present discharge power, negative value refers to pumping charge condition, P_{PV} is directly integrated PV production, $demand_{grid}$ is the grid load demand, *i* present the time interval.

To ensure the security of the reservoir, the change in pump hydro storage state is defined as:

$$S_{PHS}(i) = \eta_{pump} \sum_{i=1}^{t} pump_i + \sum_{i=1}^{t} dis_i / \eta_{dis} \quad \text{Eq 4-2}$$

The lower and upper reservoir state of pump hydro storage at any interval is limited as:

$$0.15 \cdot reservoir \le S_{PHS}(i) \le 0.95 \cdot reservoir \quad \text{Eq 4-3}$$

Where, S_{PHS} is the state of reservoir, $pump$, dis present for pump and discharge power, respectively. η_{pump} is the pump efficiency, η_{dis} refers to the discharge efficiency, capacity of pump hydro storage $reservoir$ is determined by maximum kWh to kW ratio.

The pump and discharge conditions are dependent on the simultaneously flexible demand and available PV generation, the pumping-generating scenario of pump hydro storage is optimized according to the features of daily demand curve and PV productions, pump excess PV generation (subtracting the direct integration) during daytime, then release for peak shave, pumping and discharging ability of pump hydro storage is:

$$pump(i) = \min(0.2 \cdot reservoir, \max(PV(i) - (P_{fle}(i) - 0.3 \cdot P_{fle}^{\max}), 0)) \quad \text{Eq 4-4}$$

$$dis(i) = -\min(\max(P_{fle}(i) - 0.3 \cdot P_{fle}^{\max}, 0), 0.18 \cdot reservoir) \quad \text{Eq 4-5}$$

The objective of this work is to maximize the effective integration of PV production, the pump hydro storage will absorb the surplus PV production as much as possible and discharge into minimum state by the end of daily cycle, detail operation strategy of pump hydro storage is dependent on time of days defined as follows:

$$P_{PHS}(i) = \begin{cases} pump(i), \ \mathrm{i} \subset [8:00 - 17:00] \\ dis(i), \ \mathrm{i} \subset [17:00 - 24:00] \cup [1:00 - 8:00] \end{cases} \quad \text{Eq 4-6}$$

4.3 Analysis and Discussion

4.3.1 Approach to load and production time series

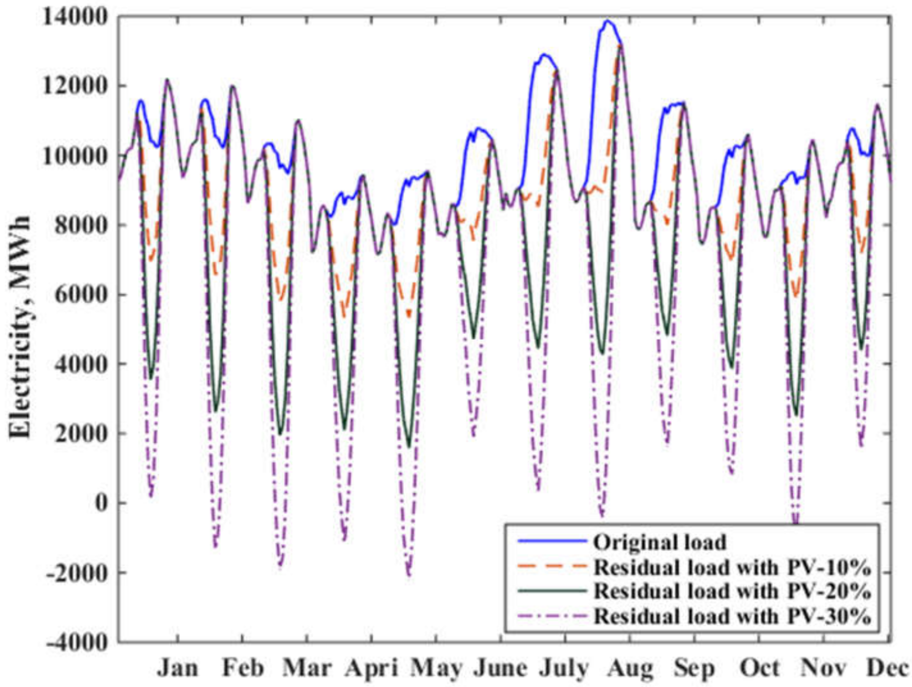


Fig.4-16. Average load and PV production in each month

Fig.4-16 illustrates the changes of residual load in each month, PV integration greatly shapes the daily demand curve and decreases the residual load during daytime, especially during the mid-season. Large-scale integration of variable PV production will raise challenges to meet the dynamic balance between electricity generation and demand at all time. Firstly, in order to reduce the time resolution and maintain the accuracy, power mix scenario for power system without pump hydro storage is analyzed according to the daily average load and PV production profiles in months described in Fig.4-16.

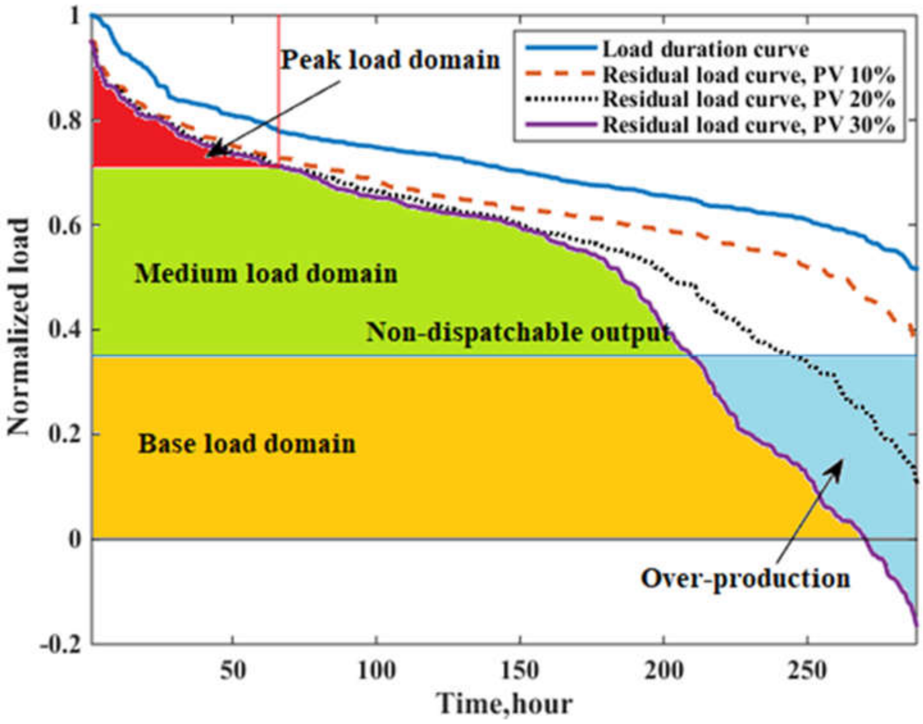


Fig.4-17. Approximation of load duration curve, resulting from daily average load and production profile in months

The load duration curves of the time series depicted in Fig.4-14 are better replicated by the load duration curve of the 1-hour history data in Fig.4-17. The selected representative days better replicate the extreme value at the upper and lower end of the load duration curve. It proves the accuracy of approximation based on selected samples, covering the time series variability and reducing time resolution. It deems that using sample composed of twelve days is sufficient to cover the characteristics of variable load and PV generation.

As the integrated PV capacity increases, simulated results indicate that PV penetration will mainly decrease the output from medium based plants, especially before 10% penetration level, curtailments will dramatically increase when further expands the integrated PV capacity due to the grid flexible constraints as shown in Fig.4-18. The fraction of load contribution fraction will become saturated with increasing integrated PV capacity, ratio of PV suppression grows. Around half of PV production has to be curtailed due to the operational limitation, when total PV production to grid load ratio reaches 30%. It indicates a profitable potential from uptake of storage system to dispatch massive PV production.

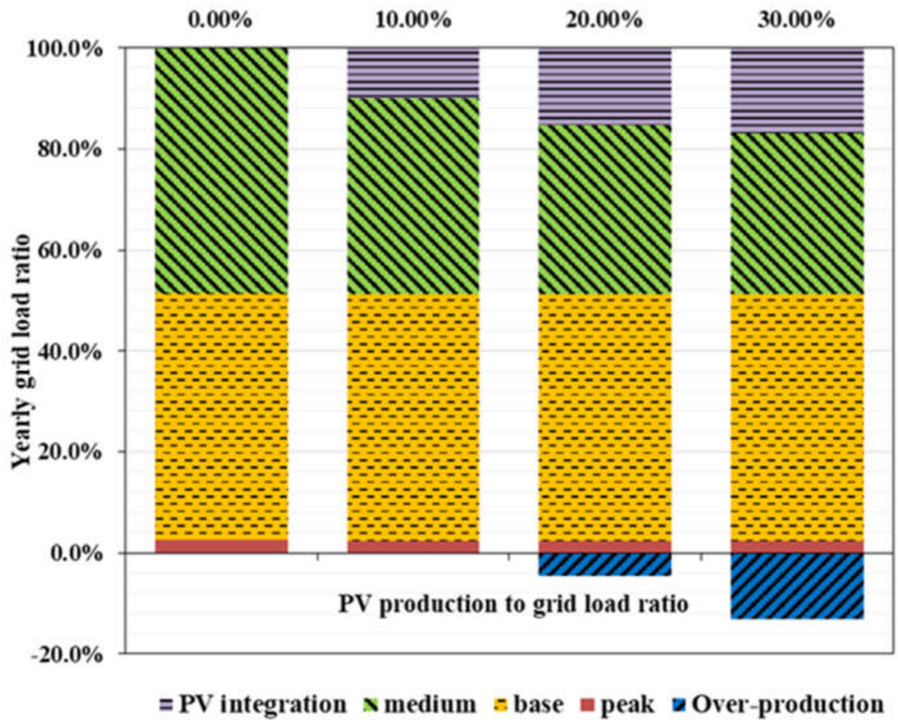


Fig.4-18. Power generation mix fraction under different annual PV production to grid load ratios, 0~30%, pumping capacity of dispatch PHS to grid peak load ratio is 0.15

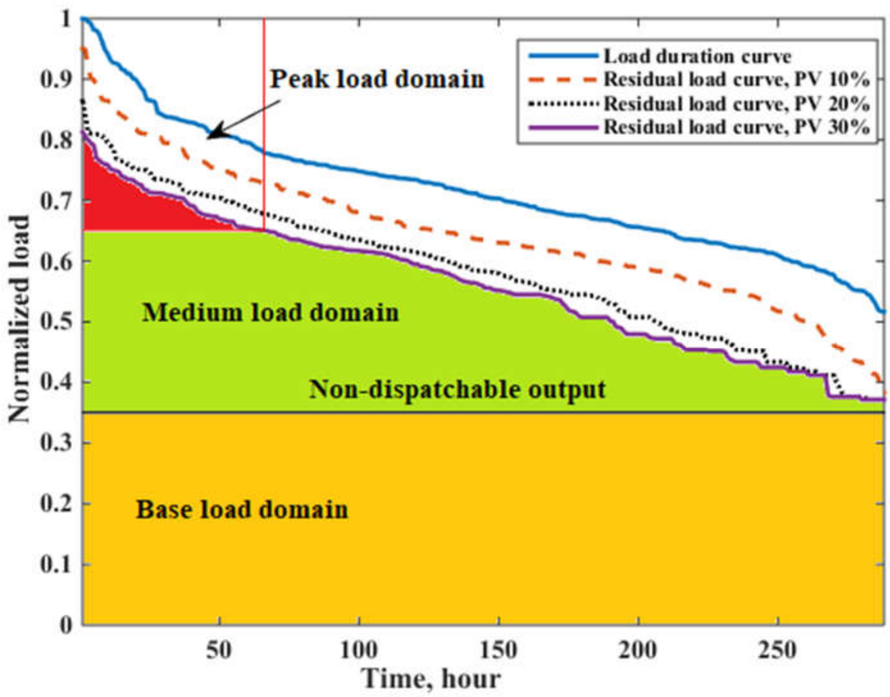


Fig.4-19. Shifted grid load duration curves for different PV capacity integration with dispatch of PHS, twelve representative days, pumping capacity of dispatch PHS to grid peak load ratio is 0.15

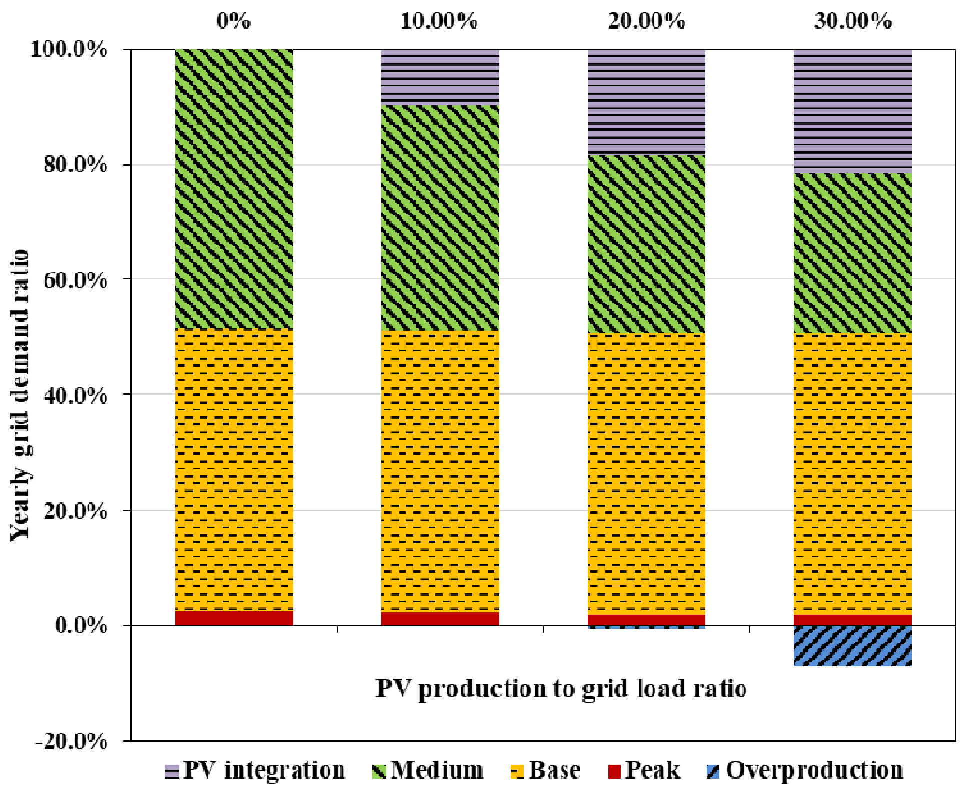


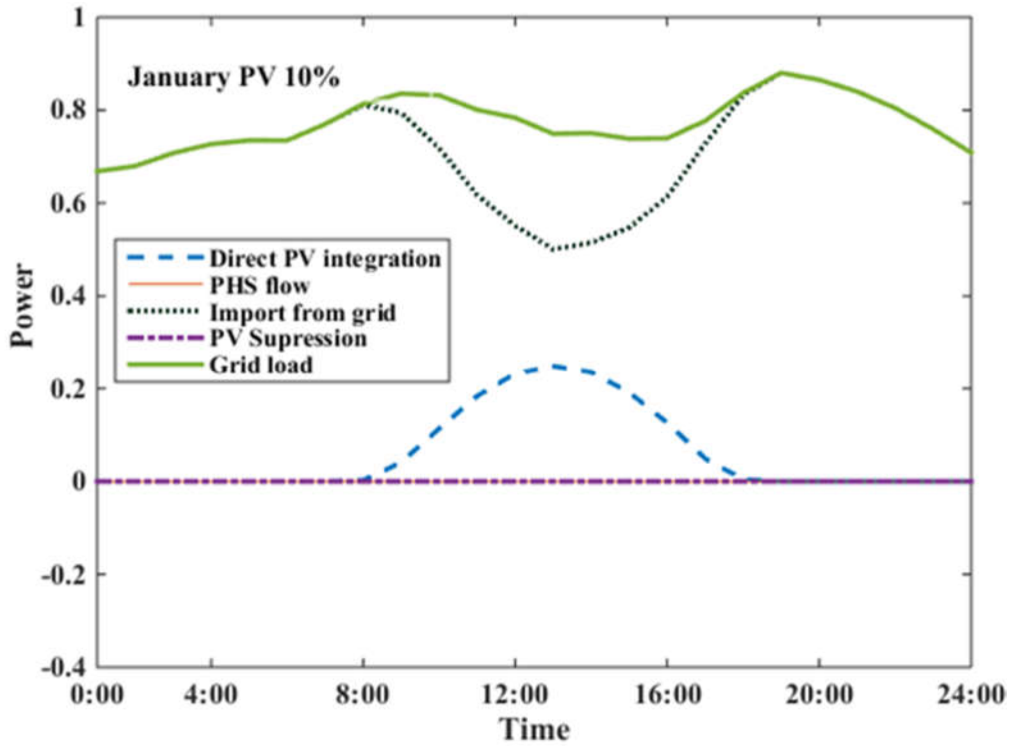
Fig.4-20. Power generation mix fraction under different anual PV production to grid load ratios (0~30%), pumping capacity of dispatch PHS to grid peak load ratio is 0.15

The pump hydro storage is added to dispatch daily the power flows pumping capacity of pump hydro storage to yearly peak grid load ratio is 0.15, recovering the surplus generation from PV and release for night peak shave or other balancing period, as a result enhancing the PV effective utilization and releasing grid peak balancing pressure. Fig.4-19 demonstrates the shifted residual load duration curves with aid of pump hydro storage dispatch under different integrated PV capacities. Fig.4-20 illustrates the changes in power supply fraction compared with the scenarios described in Fig.4-17, the pump hydro storage enhanced the PV capacity credit through mitigating peak load, in addition, recovered surplus PV production further decreases the output from the medium based domain, reduces the greenhouse gas emission from flexible thermal plants. The effective grid PV penetration level increases from 15.3% to 16.9% at 20.0% of PV production to grid load ratio. Simulation results consider the pump-discharge cycle loss and grid operational constraints (0.35 ratio of constant output, daily outputs from flexible plants vary from 30% to 100%).

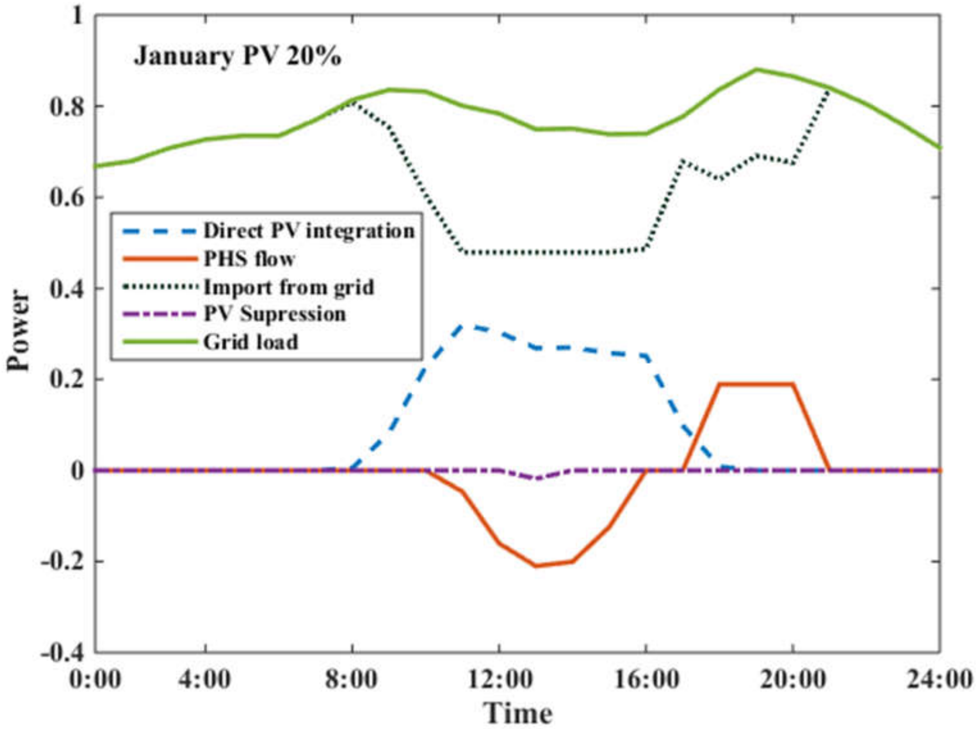
4.3.2 Load dispatch scenario

To revel the detail power supply scenarios of public grid, typical daily cycle dispatch in January are illustrated in Fig.4-21 (a-c), through varying annual PV production to grid load ratio from 10.0% to 30.0%. As presented in Fig.4-20 (a), the PV production can be directly integrated into the grid at lower penetration level, flexible generators can vary power output within their flexible range to absorb variable PV generation directly. As PV capacity increases as shown in Fig.4-21 (b), PV generation will excess the medium plant flexible limitation, surplus production triggers the pumping condition of pump hydro storage, excess PV generation can be stored for nigh peak shave usage, it indicates a promising potential to enhance PV utilization by the uptake of storage unit. A further increase in capacity of integrated PV may lead essential production curtailment due to grid flexible limitation and the upper reservoir security constraint of pump hydro storage as illustrated in Fig.4-21 (c), excess generation is over the pumping ability, state of upper reservoir has charged into its saturated condition by 15:00 p.m. part of PV generation has to be suppressed during daytime. Meanwhile, it shows a relative longer discharging period, released energy from the pump hydro storage can cover part peak load, as a whole enhance the grid flexibility.

(a)



(b)



(c)

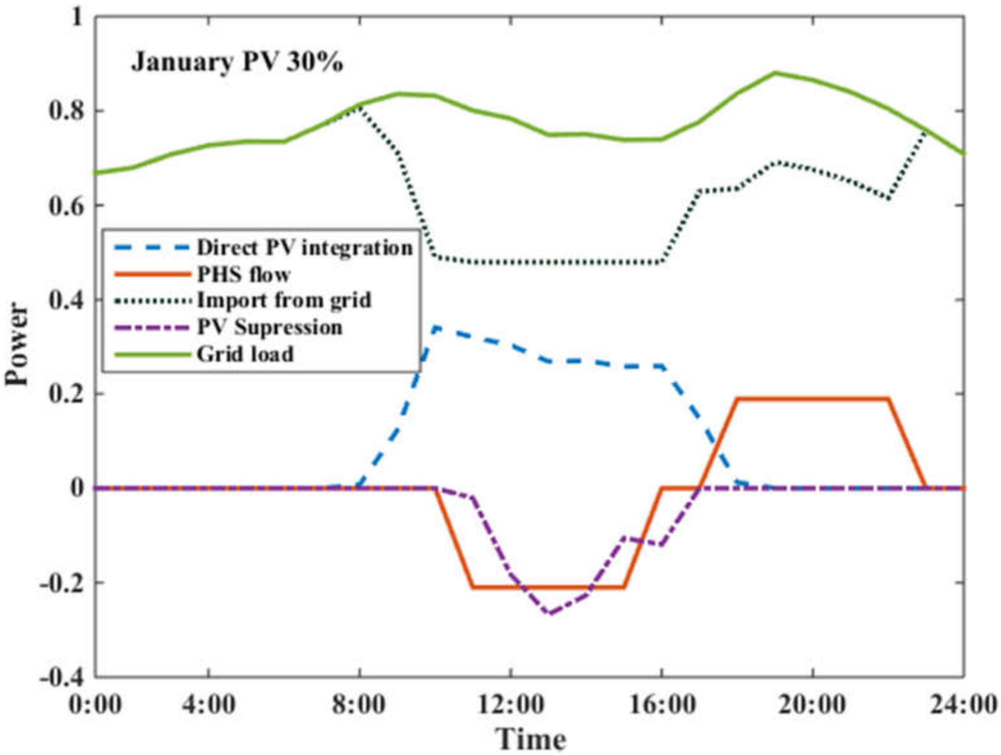


Fig.4-21. Daily power balancing flows in January for different integrated PV capacity (a-c), PV production to grid load ratio ranges from 10%~30%, pumping capacity to grid peak load ratio is 0.15

Table 4-3 The effective PV utilization ratio under different yearly PV production to grid load ratios

Ratio	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10%	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
12%	0.97	0.97	0.97	0.98	0.98	1.00	1.00	1.00	1.00	1.00	0.97	1.00
14%	0.97	0.95	0.95	0.97	0.96	1.00	0.98	0.98	1.00	1.00	0.97	0.97
16%	0.94	0.93	0.93	0.95	0.94	1.00	0.98	0.97	0.98	0.98	0.94	0.97
18%	0.93	0.91	0.90	0.93	0.92	0.98	0.97	0.95	0.98	0.95	0.92	0.97
20%	0.92	0.88	0.83	0.91	0.86	0.98	0.95	0.92	0.96	0.95	0.90	0.94
22%	0.88	0.81	0.79	0.87	0.80	0.96	0.92	0.86	0.96	0.93	0.87	0.92
24%	0.85	0.77	0.74	0.83	0.75	0.95	0.86	0.81	0.94	0.91	0.82	0.92
26%	0.79	0.72	0.67	0.76	0.71	0.93	0.81	0.74	0.92	0.89	0.78	0.89
28%	0.75	0.68	0.64	0.71	0.64	0.91	0.77	0.69	0.88	0.85	0.72	0.86
30%	0.71	0.64	0.59	0.68	0.60	0.88	0.71	0.65	0.83	0.80	0.68	0.83

Ratio refers to annual PV production to grid load ratio

Table4-3 lists the variations of PV utilization scenario in months over a year, with aid of pump hydro storage that pumping capacity to grid peak load ratio is 0.15, demand load can directly absorb the PV production at relatively low integrated PV capacity, air condition demand provides a good coincides with the daily PV productions in summer, the overproduction will firstly occur in mid-seasons, due to the mismatch between generation and load profiles and flexible limitation. As PV capacity continues to increase, the pump station reached its maximum ability to recover the surplus PV production, pump cycle loss and curtailment will jointly decrease the effective PV integration.

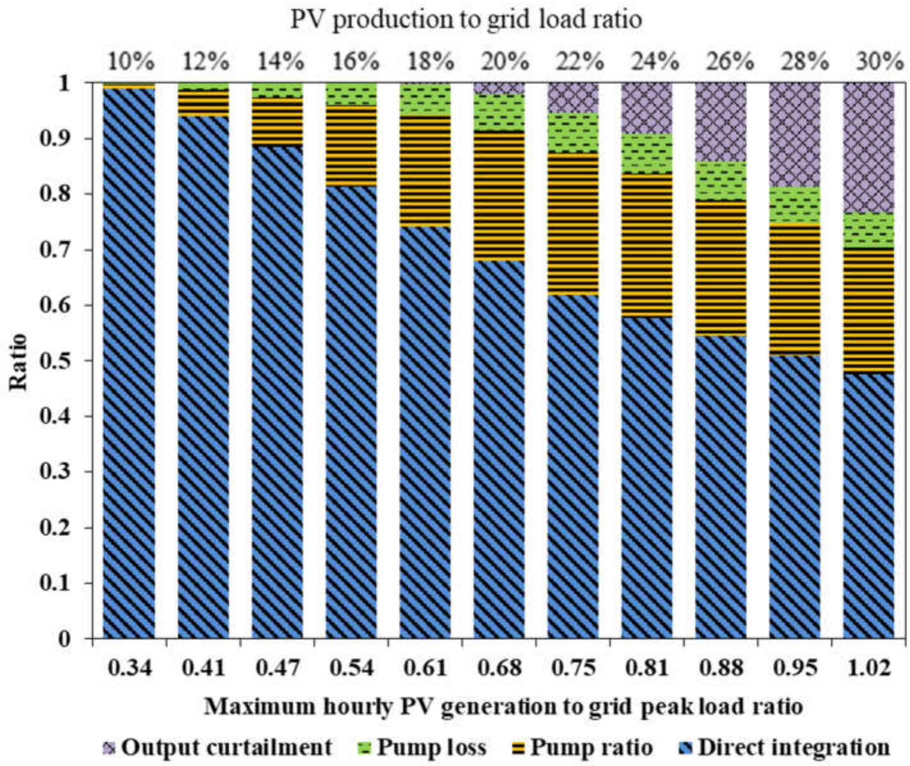
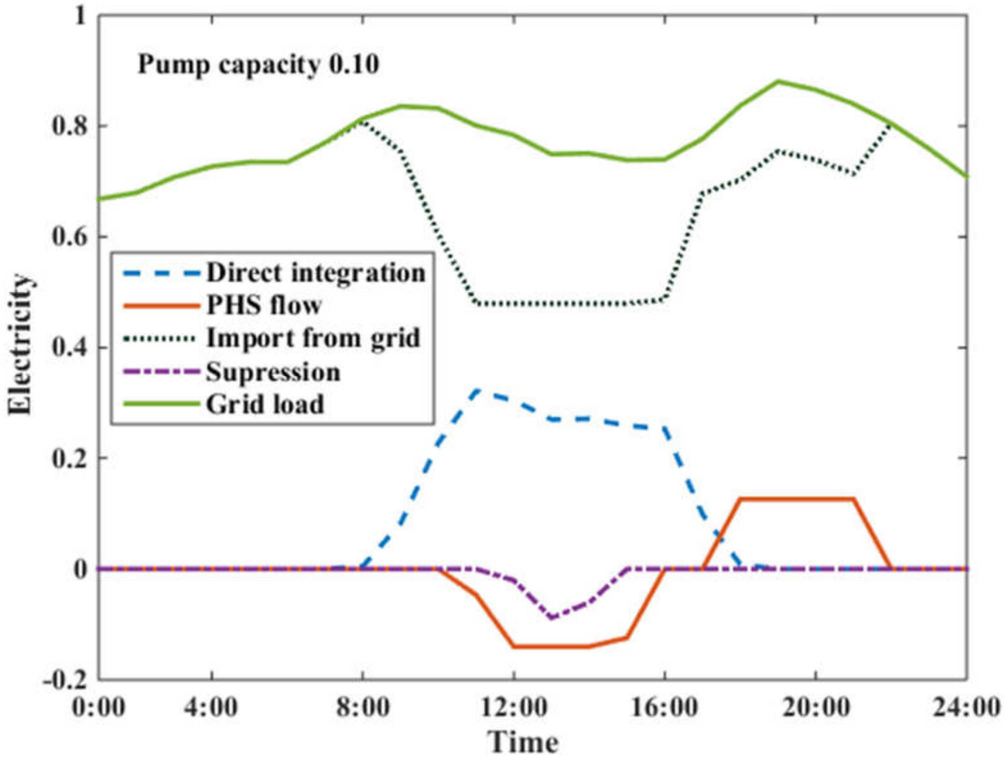


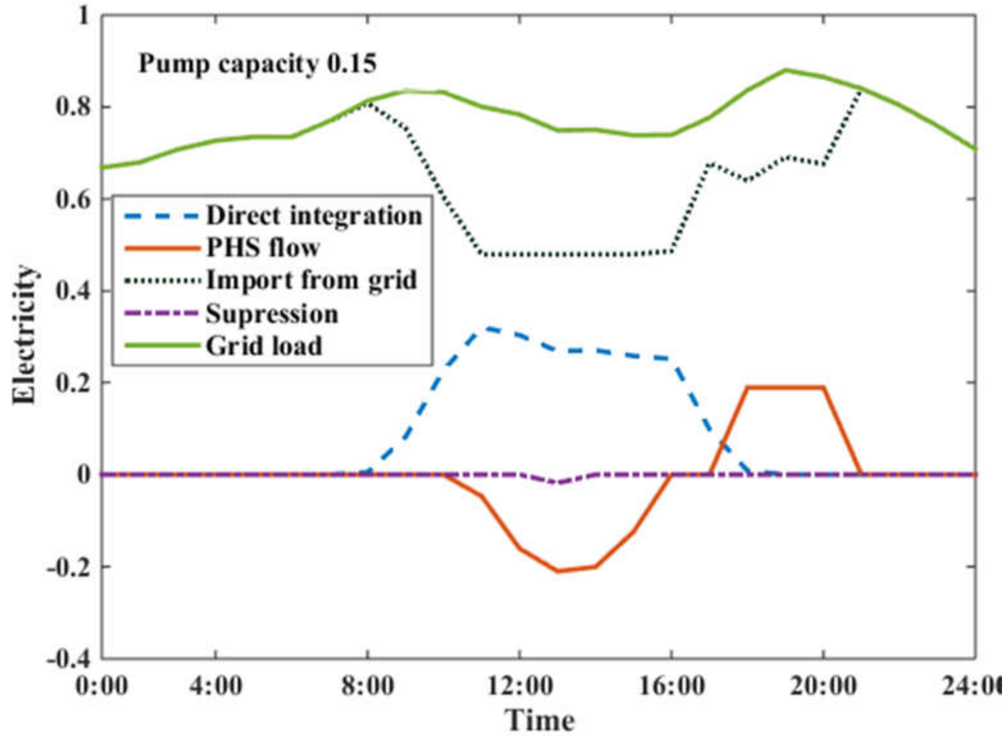
Fig.4-22. Utilization fraction (effective integration, pump cycle loss and output curtailment) of PV production as a function of relative integrated PV capacity, capacity of PHS to peak load ratio is 0.15

Fig.4-22 illustrates the detail changes in yearly PV utilization fractions with dispatch of proposed pump hydro storage. The direct consumption ratios drop with expanding integrated PV capacities, pump ratio refers to the recovered surplus PV production, pump cycle loss increases in linear with increasing pumped energy during supply-demand balancing cycle process. Output curtailment increases under higher integrated PV capacity due to the limitation of grid flexibility, it has accounted for a large ratio of PV generation when maximum PV generating capacity is nears to the peak grid load value.

a)


Pump capacity 0.10
Direct integration
PHS flow
Import from grid
Supression
Grid load
Electricity
Time
1
0.8
0.6
0.4
0.2
0
-0.2
0:00
4:00
8:00
12:00
16:00
20:00
24:00

b)


Pump capacity 0.15
Direct integration
PHS flow
Import from grid
Supression
Grid load
Electricity
Time
1
0.8
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c)

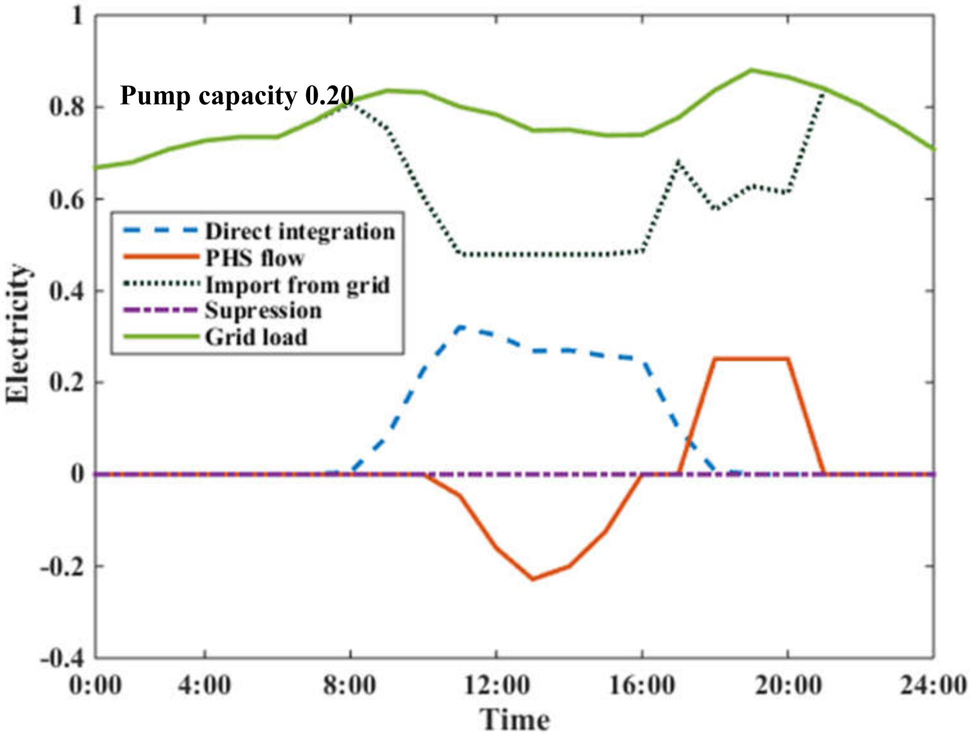
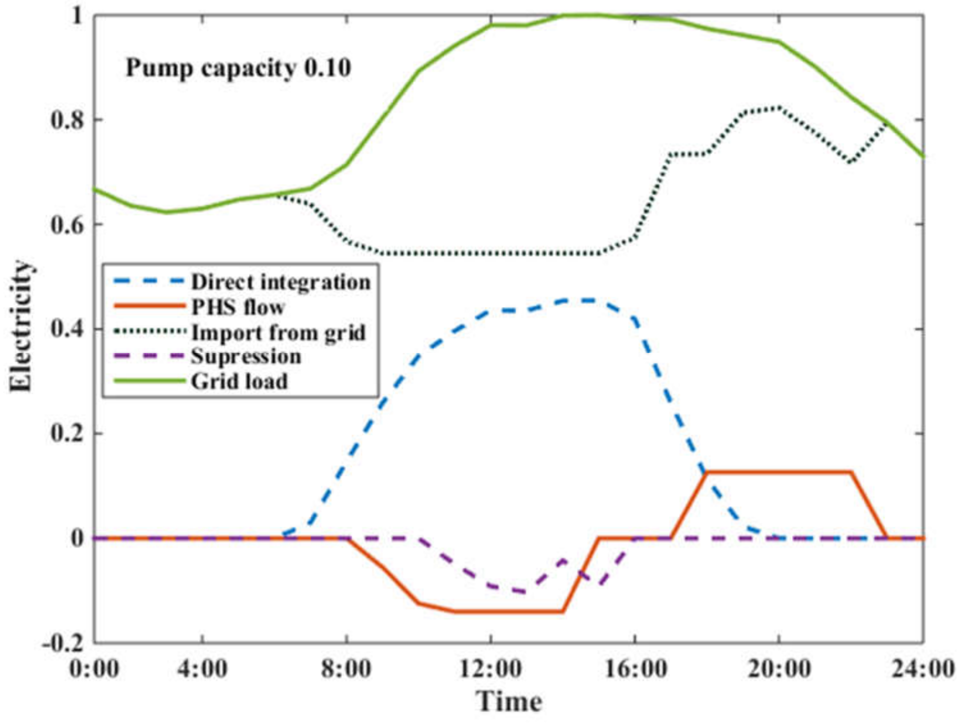
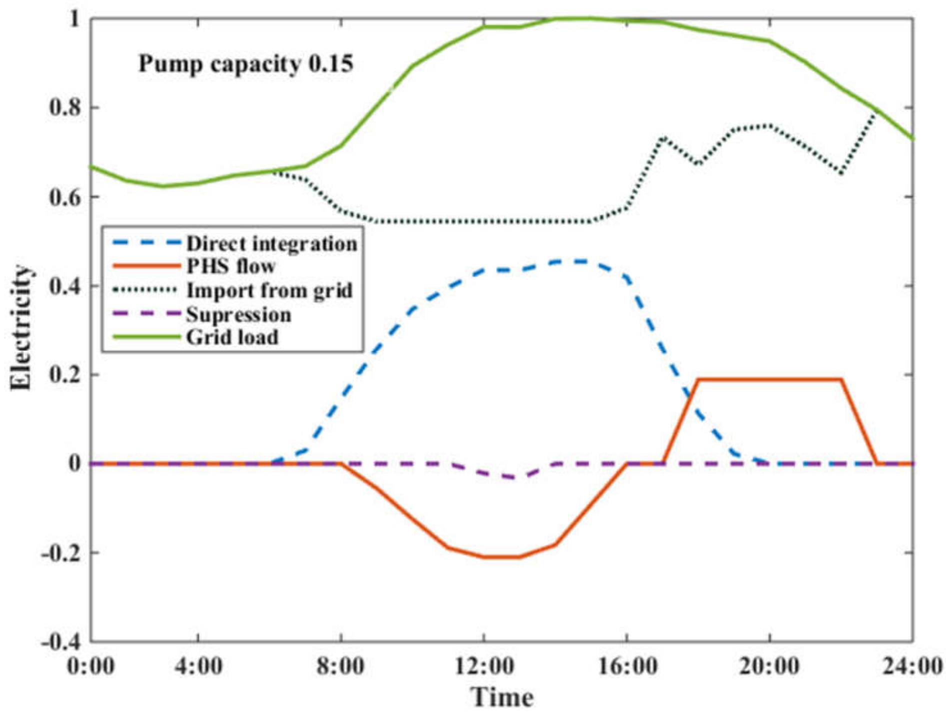


Fig.4-23. Daily power balancing flows in January for different integrated PV capacity (a-c), PV production to grid load ratio at 20%, pumping capacity to grid peak load ratio at 0.10 (a), 0.15 (b) and 0.20 (c)

a)



b)



c)

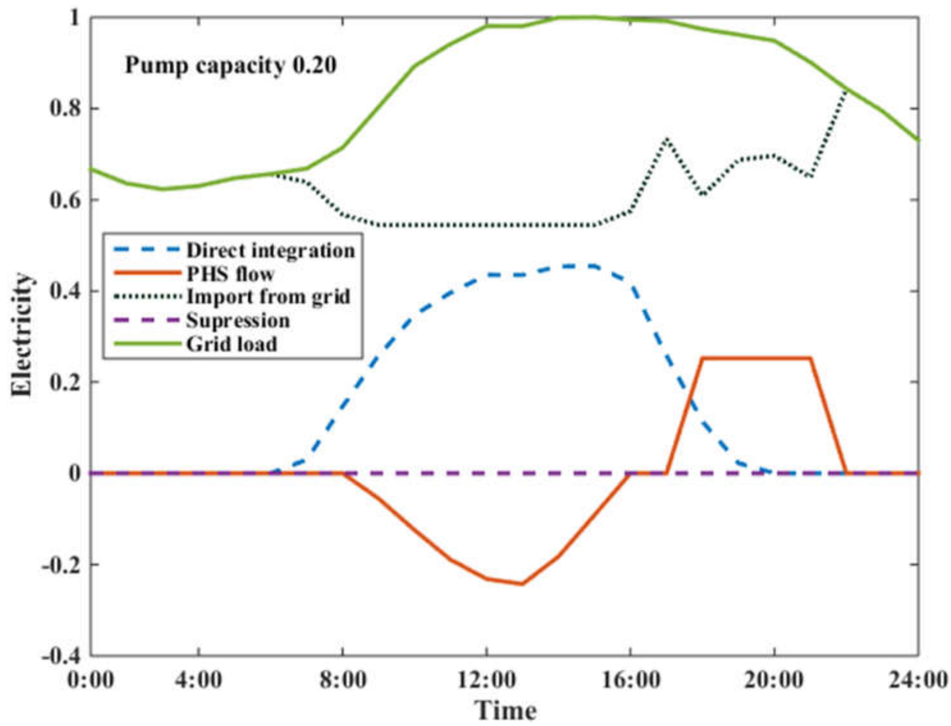


Fig.4-24. Daily power balancing flows in August for different integrated PV capacity (a-c), PV production to grid load ratio at 20%, pumping capacity to grid peak load ratio at 0.10 (a), 0.15 (b) and 0.20 (c)

It is also useful to evaluate the impact of pump hydro storage's maximum pumping/discharging power (storage ability) on grid load dispatch and PV utilization. In order to examine the dispatch role of pump hydro storage system, this part simulated the detail of supply-demand balancing process via varying pump capacity (pump ability to grid peak load ratio). Set PV generation to grid load ratio at 20%. Fig.4-23 (a)-(c) illustrate the dispatch scenarios of power flow based on daily average load and generation in January, including power flows of PHS, PV plant and grid. For a given fixed PV production, the directly integrated PV production is constant. At lower pumping ability (a), great part of PV production has to be curtailed considering reliable grid flexibility. Curtailment is becoming less with increasing pumping ability, stored energy could effectively shave the peak load in night (17:00-22:00) in absence of PV production. Therefore, enhancing the grid flexibility and PV utilization on daily basis. Fig.4-24 (a)-(c) illustrate the dispatch scenarios of power flow based on daily average load and generation in August, including power flows of PHS, PV plant and grid. PV shows higher generating ability during summer period compared with January, higher correlation between PV generation and load profiles enable higher direct consumption. Part of PV has to be curtailed at lower uptake capacity of pump hydro storage due to the limitations of grid flexibility and pump upper reservoir (a), increasing pump ability helps to recover the PV suppression, then releases stored energy later use further decrease the peak load grid in absence of PV production.

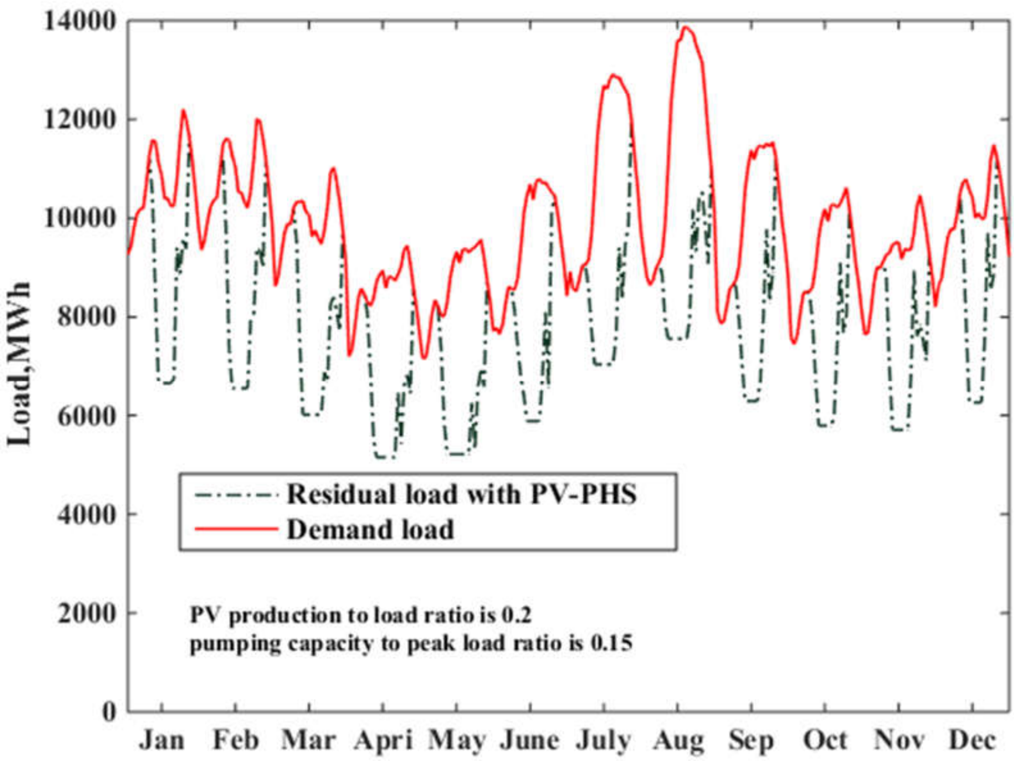


Fig.4-25. Daily demand load and residual load profiles with PV-PHS, PV production to load ratio is 0.2, pumping capacity to peak load ratio is 0.15

Fig.4-25 presents the average daily load and residual load profiles with PV-PHS in each months, with PV production to load ratio is 20% and pumping ability to peak load ratio is 0.15. PV production has greatly shaped the residual load curve with aid of pump hydro storage system, grid load generally has reached their grid flexibility (output of flexible generators ranges from 0.3 to 1.0) during midday time, due the large feed-in PV production, especially during the mid-season period.

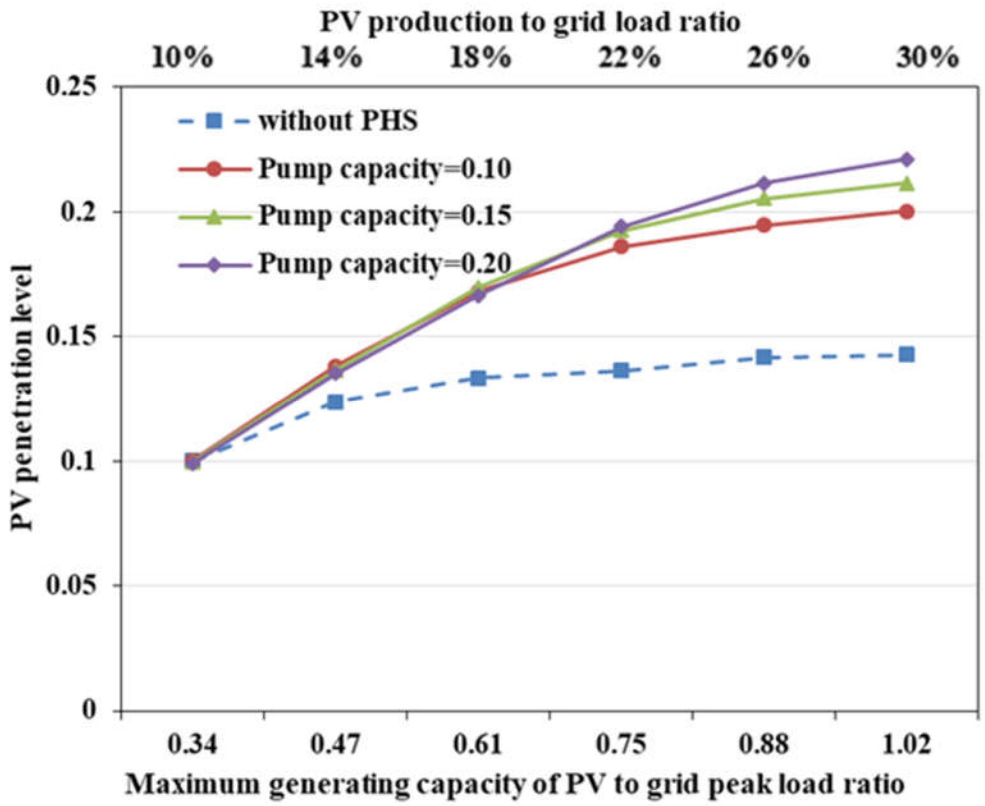


Fig.4-26. Impacts on effective PV integration of different relative PV capacity with different pumping capacities of dispatch PHS

As integrated PV capacity continues to grow, pump hydro storage as the main dispatch unit, its capacity may expand further. Fig.4-26 shows the effects of combining pump hydro storage and PV on the variations of yearly effective PV penetration level, and compares the scenarios of different pump hydro storage capacities, the pumping ability varies from 0.1 to 0.2 ratio of grid peak load. Without pump hydro storage in dash line, as generating capacity of PV increases up to 0.55 of peak load, the PV penetration level become saturated, and suppression increases significantly to increase PV capacity. The maximum PV penetration merely reaches 14.3% at total PV output to load ratio is 30.0%. Percentage increases in PV integrated penetration level with pump hydro storage dispatch can be clearly seen in Fig.4-26, there is little differences in initial PV penetration values, most of the PV production could be directly consumed in the grid. Then more excess PV production could be stored in the pump hydro storage with the increasing relative PV capacity, PV integration ratio increase obviously with storage dispatch. With relative small storage capacity, PV penetration degree firstly comes into saturated condition with increasing integrated PV capacity. It can be explained that as PV capacity expands pump hydro storage with less capacity earlier reaches its saturated condition, it means that more surplus production has to be suppressed. Pump hydro storage station with a greater pumping ability can absorb more surplus PV production during daytime. It is worth to note that at the same integrated PV capacity, enhancements in PV penetration level become less obvious with increasing pumping capacities of pump hydro storage, it could be explained by increasing pumping cycle loss and great surplus PV generation rises from grid security.

4.3.3 Levelized cost of PV-PHS electricity

This section evaluates the economic performance of PV-PHS system from the levelized cost of electricity (LCOE) perspective.

Fig.4-26 shows the impacts on LCOE by applying different pump hydro storage capacities to the different relative integrated PV productions for the condition of Table 4-4. Note that there are twice replacement of PV system after its lifetime period. In long term run, LCOE of hybrid PV-PHS system is calculated as follow:

$$LCOE = \frac{\sum_{t=1}^{N} I_{PHS} + I_{pv}(1 + 1/(1+r1)^{\wedge}t1 + 1/(1+r1)^{\wedge}t2) + OM_t}{\sum_{t=1}^{N} E_t / (1+r2)^t} \quad \text{Eq 4-7}$$

Where, $r1$ is capacity investment discount rate, 2%. $r2$ refers to PV output discount rate, 1%. t presents the generic year in [1,2,3,…, N], I present the capital investment including PV and pump hydro storage, t1, t2 present the twice replace time of PV system, OM presents the operation and maintenance costs, E is the annual effective integrated PV production.

Due to the higher initial capital, the LCOE of PV-PHS system may be hard to achieve benefits compared with only PV system at relative lower integrated PV capacity. As the integrated PV capacity increases further, LCOE in absence of storage increases sharper, it can be clearly seen that LCOE line can lie below the scenario of without storage. Pump hydro storage system helps slow down the increase in overall LCOE. It can be explained by the fact that pumped storage system recovers a part of surplus PV production to increase effective PV utilization. The profitability can increase to cover the initial capital pump hydro storage investment as PV production increases, Pumped storage station with higher pumping capacity shows the economic advantage at larger integrated PV capacities, as illustrated in Fig.4-27.

Table 4-4 Economic parameter of PV and PHS in power system

Variables	Value
PV plant cost, $/kW	3500
PV Lifetime, years	20
PHS capacity cost, $/kW	2400
PHS lifetime, years	60
Annual O&M cost rate	0.01

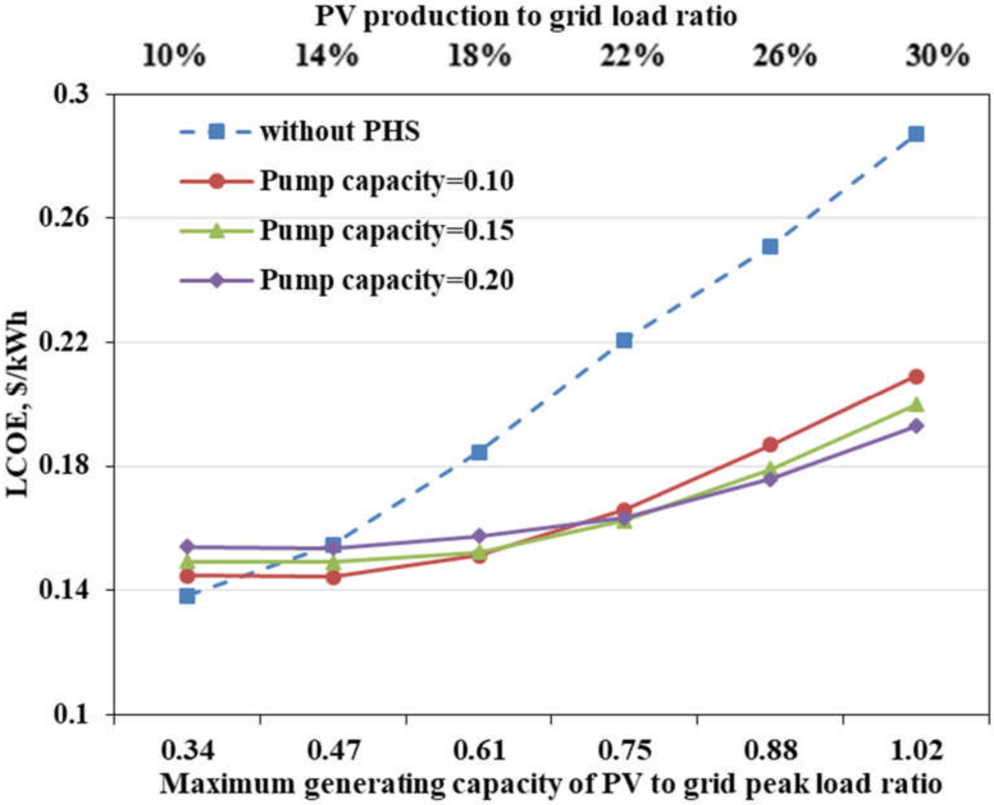


Fig.4-27. The average lifetime levelized cost of electricity generation for PV systems with different integrated pumping capacities of PHS

4.3.4 Electricity market impact

The power generation costs of plant for each power source are obtained by dividing total costs by the amount of power generated. In plant viewpoint, total cost is composed of capital cost, operating and maintenance costs, fuel cost and public costs. Public costs refer to accident risk, policy measures and environmental measures. The detail components of each cost are illustrated as following:

- Capital cost

Total construction costs, fixed asset tax, water utilization charges, facility disposal cost.

- Operating and maintenance costs

Total personal expenses, repair costs, miscellaneous expenses, and work sharing costs.

- Fuel costs

Value obtained by multiplying fuel price per unit quantity with required fuel amount, in case of nuclear energy refers to fuel cycle costs.

- CO_2 reduction costs

Costs required for reduction of CO_2 emissions in the use of fuel for power generation

- Safety and risk cost (nuclear power)

Costs for safety improvement effort and accident risk.

- Costs for policy measures

Not cost born by power generation companies for power generation, but public costs considered necessary power generation by each power resource out of the costs for policy measures covered by tax.

Fig.4-28 shows the detail components of power generation cost by each power source in 2014, capacity factors for nuclear, thermal plant, hydro power, wind and solar are 70%, 70%, 45%, 20% and 14% respectively. Policy efforts are expected to reduce fossil fuel price, technical innovation will reduce the capacity costs of renewable energy resources (3,4).

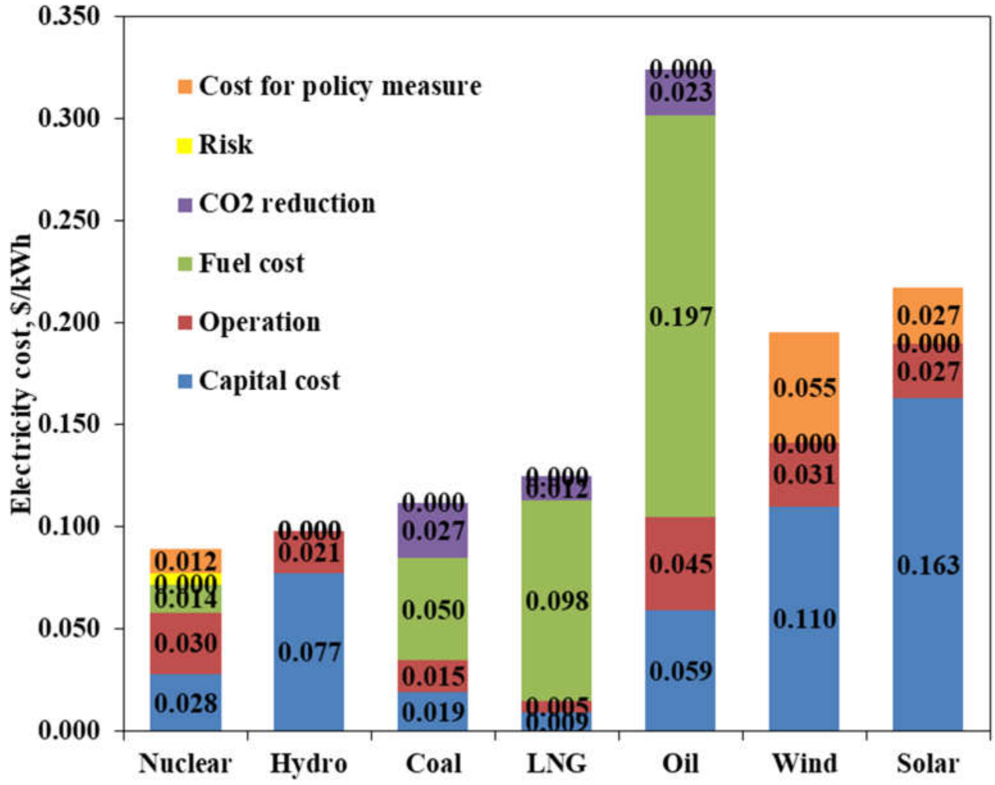


Fig.4-28. Power generation costs by sources in 2015, Japan

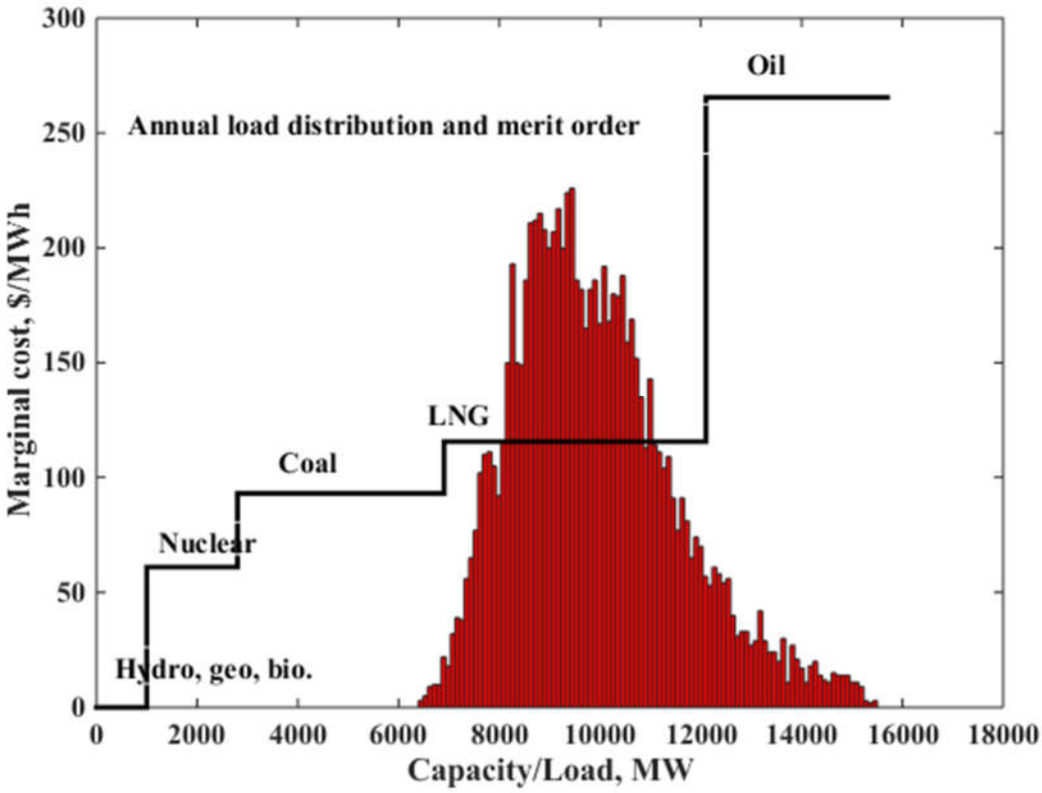


Fig.4-29. Power supply merit order curve and annual load distribution in Kyushu

At current electricity market in Kyushu, greater part of power is produced by centralized power plants. Fig.4-29 displays the supply curve for conventional plants and annual load distribution of Kyushu in 2017. Basically, the marginal costs of a conventional power plant depend upon its net efficiency, the respective fuel and CO_2 emission costs, and variable operating and maintenance costs. Supply curve presents the minimum price at which a producer is willing to produce a certain quantity of power. By linking merit order curve and load duration curve, it is possible to determine the applicable prices for electricity (for the hourly amounts of demand in a year). Electricity pricing for each MW supplied, as identified from the merit order curve, are assigned to respective electricity demand of the load duration curve. Electricity prices for demand quantities are allocated to the corresponding duration in hours. The differences in the impact on market prices is caused by the different step size of the Kyushu merit order curve in different load segments of the electricity demand. Marginal cost is higher at peak load, the peak demand price will be set at higher level to cover the capacity cost of peak-meet generators.

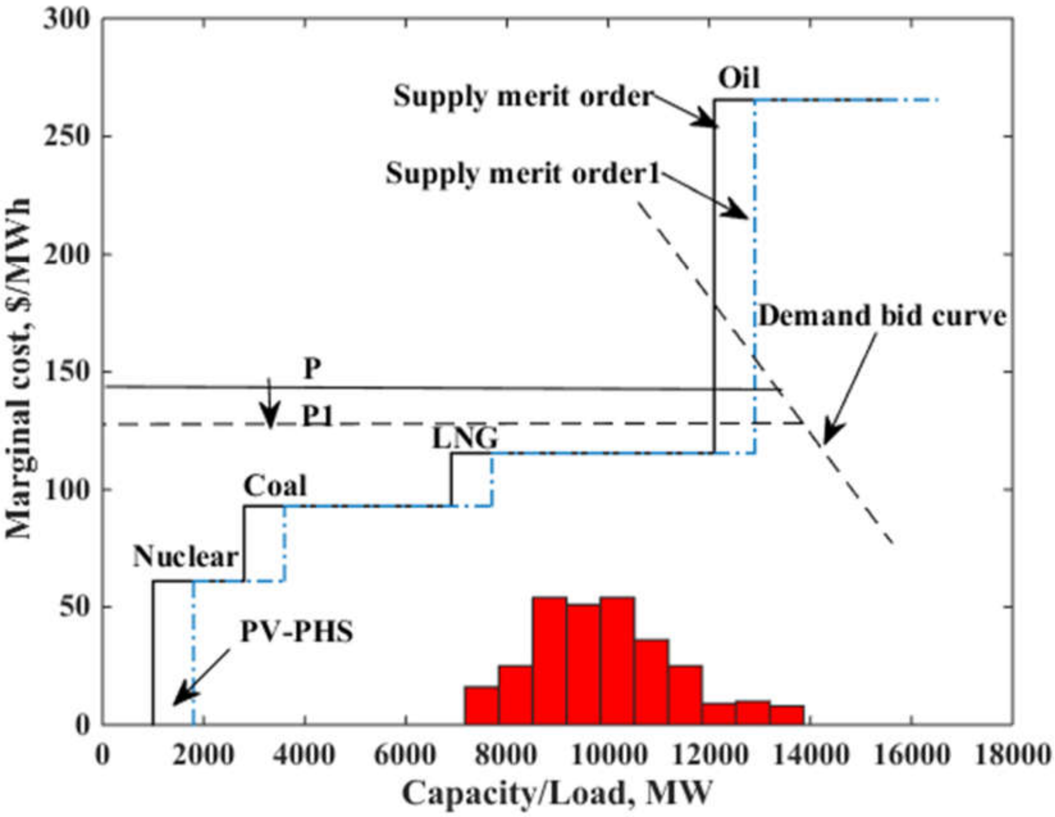


Fig.4-30. Merit order effect of PV-PHS in Kyushu power supply system

In general, renewable energy has minimal marginal costs in form of variable operating and maintenance costs. Typically, when the renewable energy is feed into the grid, this leads to significant changes in merit order curve. Given the specific Kyushu electricity market condition, analysis focuses on merit order effect of PV-PHS plant. Set PV production to load ratio 20% and pump ability is 0.15 to peak load ratio. Fig.4-30 presents a simplified representation of price setting mechanism and illustrates the impacts when PV-PHS is added to power system on hourly average load in each month on annual basis. Give priority to the PV-PHS plant, solar power will enter near the bottom end of the merit order, merit order effect of PV-PHS is stronger on peak demand hours, and causes a shift in merit order supply curve to the right (the dash dot line), reducing the market clearing pricing (from P to P1) corresponding to the demand bid curve.

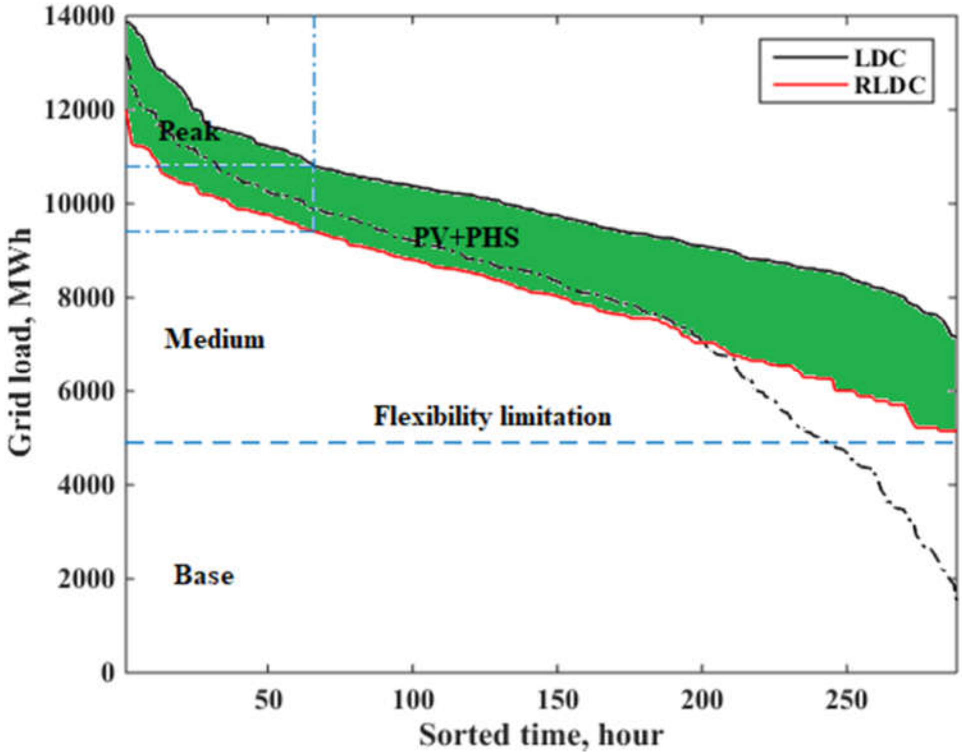


Fig.4-31. Impacts of PV+PHS on load duration curves, dash dot line refers the residual load duration curve without PHS

Based on the simulation model in section 4.2.3, the dispatch scenario of public grid is simulated under scenario of PV production to grid load ratio 20% and pumping ability to peak load ratio 0.15. Load duration curve is generally used to quantify the effects of variable renewable integration, such as matching prosperity, induced challenges. Fig.4-31 illustrates the impacts of PV-PHS on residual load duration curve, dash dot line refers the residual load duration curve without PHS dispatch. Due to the natural intermittent, solar PV plant contributes different parts of the load from the peak load to baseload, and shows a low peak capacity credit as shown in the dash dot line. The higher PV penetration reduce the full load hours of flexible power plants, the overproduction has occurred at the right bottom part of the residual load duration curve. Uptake of PHS enhances the peak capacity credit of PV plant via power dispatch process, and transfers the PV curtailment under the flexible limitation line to medium load part, increasing the overall PV penetration level in the grid. As demonstrated in Fig.4-32, PV integration greatly changes the fraction ratio of power supply system, ratio of other resources in medium region drops from 48.0% to 29.9%.

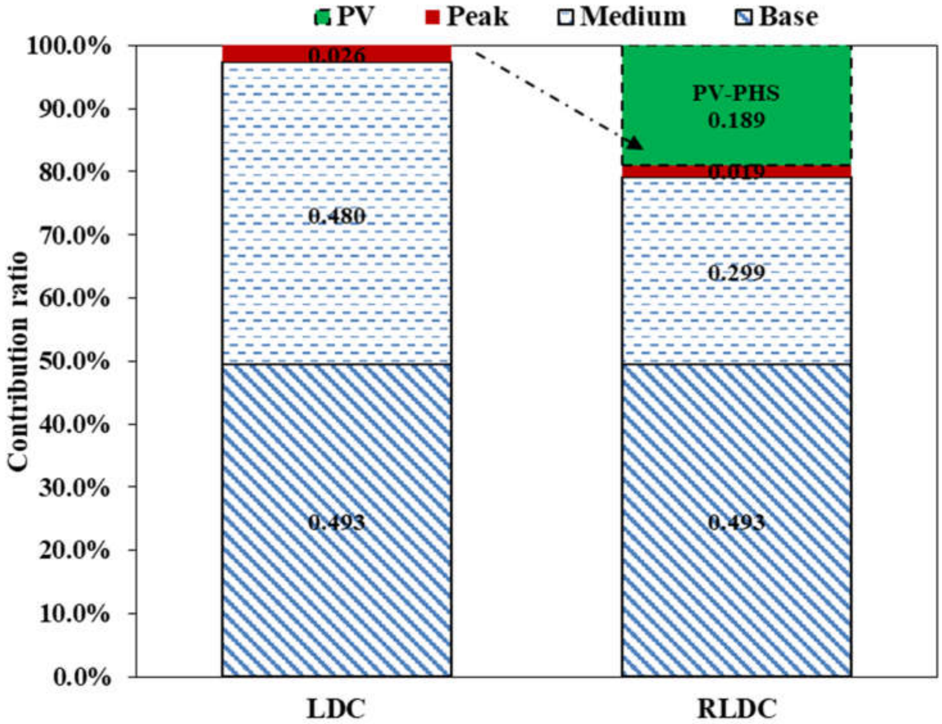


Fig.4-32. Impacts of PV-PHS on the contributions of power supply

Considering a time varying demand, the annual cost per unit capacity for each power supply technology is a mix of capital investment, operation and maintenance, and fuel consumption costs. The cost screen curve as a function of the number of annual production hours, and the slope of the cost curve presents the variable components including fuel, operation and maintenance. The screen curves are usually used to determine the cost efficient power supply technology. At lower value of operation time, the annualized capital cost dominates overall cost, technology features with higher variable cost increases more with increasing operational time.

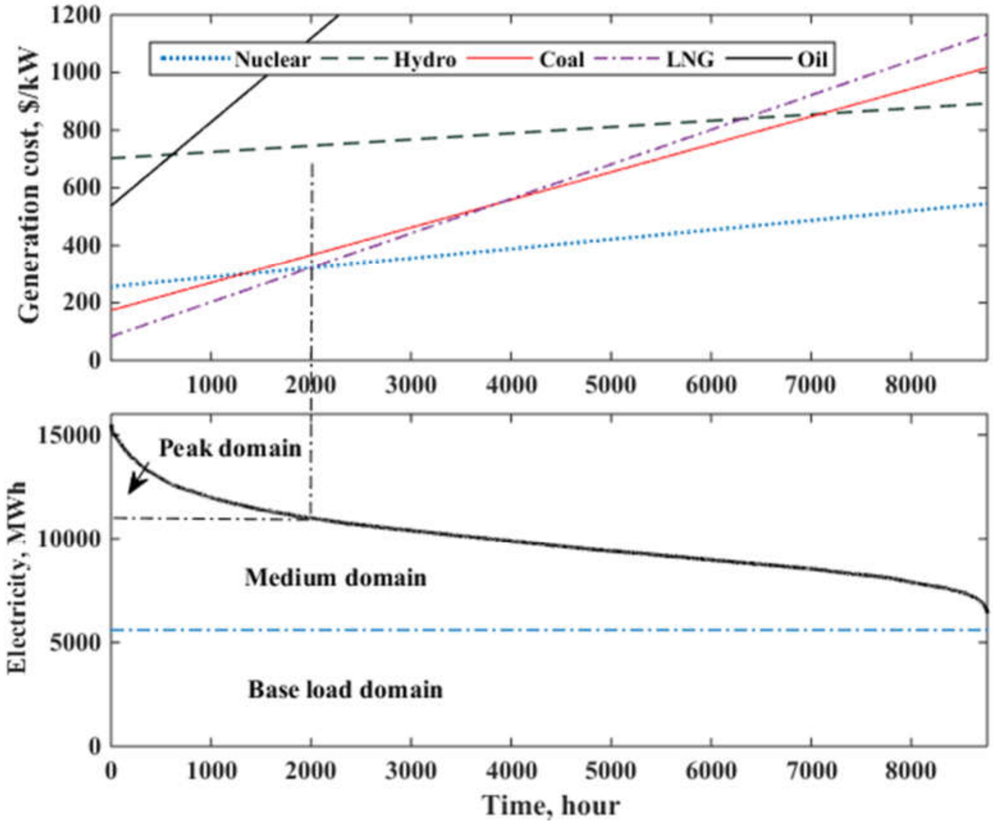


Fig.4-33. Annual cost per unit capacity and composition of power resource

According to the cost information of power technology in Fig.4-27, the upper chart of Fig.4-33 shows the annual costs of power technology per kW by resource (3), total cost as a function of period of use. The bottom part depicts the hourly electricity demand in MW in descending order for entire 8760 h of a year. Combination of load duration curve and cost curves is utilized that makes it possible to model cost-effective composition of a conventional power plant complex. Oil or LNG based thermal plant is cost-efficient technology for peak-meeting generator with shorter run period. LNG and coal based plants will generally serve as flexible plants to follow the variations in time series load. Hydro plant shows advantages from whole year operation perspective without fuel consumption. Nuclear plant and coal based plants show an economical advantage in long time operation, those technologies are suitable for non-dispatchable technology with constant output.

Under current Kyushu power resource structure, Coal and LNG based thermal generators are responsible for the medium load region. Coal, geothermal, biomass, run of river and nuclear power plant serves as base load technologies, oil power plant is able to operate particularly flexibly and are hence utilized to meet the highest demand during a day.

Table 4-5 Simplifies power fraction ratio of power supply resource

Type	Peak		Medium		Base		Total	
	A	B	A	B	A	B	A	B
Nuclear	0%	0%	0%	0%	15%	15%	15%	15%
LNG	0%	0%	38%	26%	0%	0%	38%	26%
Coal	0%	0%	10%	4%	26%	26%	36%	30%
Oil	3%	2%	0%	0%	0%	0%	3%	2%
Hydro	0%	0%	0%	0%	5%	5%	5%	5%
PV-PHS	0%	1%	0%	18%	0%	0%	0%	19%
Others	0%	0%	0%	0%	3%	3%	3%	3%

Combined to the load duration curve and cost curve of each power technology, set the coal and LNG based generators as flexible medium power technologies. The detail power fraction ratios are illustrated in Table 4-5, A presents the original load total covered by conventional plants, B presents scenario with PV-PHS, solar PV production mainly decreases the power load in medium region.

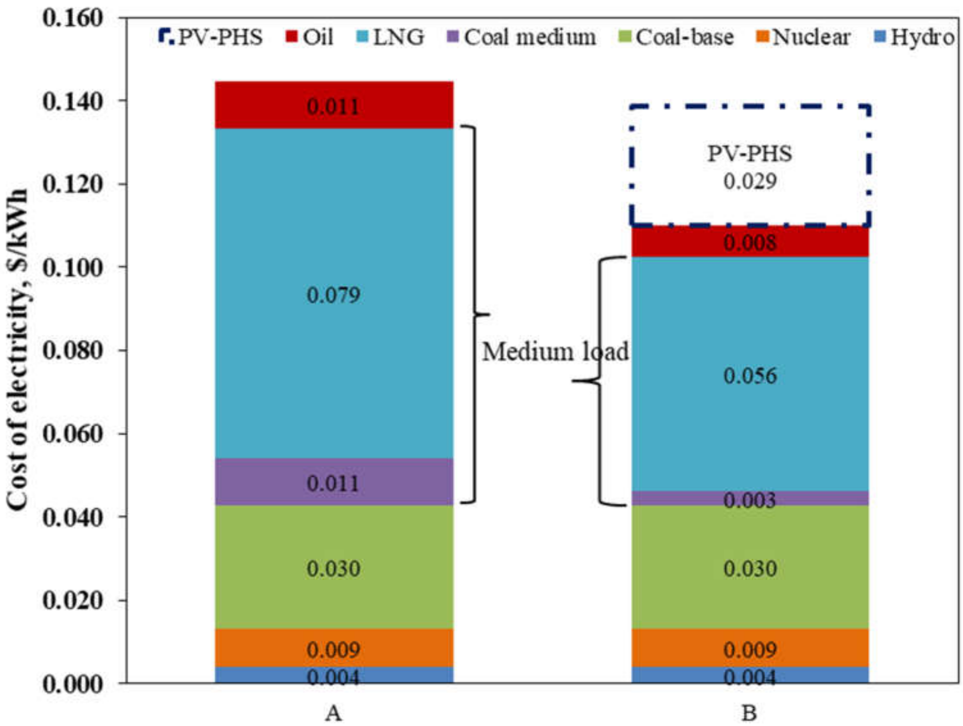


Fig.4-34. Comparison of electricity generation cost between different power mix struture

Electricity generation costs are calculated based on the detail cost parameters of each power technology in Fig.4-28. Ignoring the components from geothermal, biomass and wind with less contribution to Kyushu power system, Fig.4-34 illustrates the detail cost composition of power generation in kWh, composed of capital cost and marginal costs (fuel, operating and maintenance, risk and CO_2 cost) for scenario A and B, respectively. PV-PHS integration mainly reduced the marginal costs in sector of medium load region, mainly composed of LNG and coal based thermal generators. The cost of electricity in kWh drops from 0.145$/kWh to 0.139$/kW, considering the levelized cost of PV-PHS is 0.15$/kWh (PV production to load ratio is 20%, pumping ability to peak load ratio is 0.15 described in section 4.3.3).

4.4 Summary

There is a increasing trend in renewable integration in plant side, the VRE intermittent output has a great influence on grid supply-demand balance, especially under high renewable energy penetration level. Performance investigation of VRE further integration can help utility understand electricity market investment plant and structure optimization. This section uses the real monitored load and power resource data to explore the performances of Kyushu public grid with massive PV integration, meanwhile examines dispatch role and economic performance of PV-PHS.

Due to the grid flexibility constraint and low correlation between solar generation and load profiles, the PV production can greatly shape the grid residual load, PV integration mainly decreases the output from medium based plants. Due to stochastic nature, PV shows low peak capacity credit. Overproduction has occurred when yearly PV production to grid load ratio excesses 10.0%, and around 50.0% of PV production will be curtailed when increases ratio of maximum PV generating capacity to grid peak load to 1.02.

Pump hydro storage can play an effective role in promoting PV utilization and maintaining the grid flexibility via absorbing excess PV generation, and release stored energy for peak shave, especially during mid-seasons and winter periods. Applying pump storage increases the PV penetration level and further decreases the output from medium plants generally including flexible plants (generally is composed of LNG, Coal). Meanwhile the PV peak capacity credit can be enhanced. Considering technical and grid flexible constraints, PV effective integration could be obviously enhanced with dispatch of pump storage system, for a given capacity of pump hydro station, the increase rate in penetration degree will become less with increasing integrated PV capacity.

According to the dispatch scenario, for given capacity of hydro pump storage, pumped energy increases with increasing PV production, hence enhancing the utilization ratio of pump storage. Add pump storage system could effectively increase the PV penetration via recovering suppression due to grid flexibility limitation. PV production and load profile show great variations over a year, PV production shows high peak capacity credit in summer due its high correlation with demand load.

Economic performances of different pump hydro storage capacities are analyzed from long-term run perspective, apart from the flexible production and reserve equipment, profitability from recovering surplus PV generation is able to cover the investment of storage unit, pump hydro storage with relative large size shows economic advantage at larger scale PV integration.

The merit order effects of PV integration is illustrated in supply curve, renewable energy integration can influence the energy market. PV-PHS effectively, shifting the curve to right. Combination of cost curve and load duration is utilized to determine the power technologies in different sector of load duration curve, and evaluate the impacts of PV-PHS on energy market. PV-PHS reduced the contributions from medium load region, reducing the marginal costs of LNG or coal based generator. Under current market condition in Japan, overall electricity generation cost is 0.139$/kWh at PV penetration level at 18.9% with dispatch of pump storage system. Further cost drop in PV generators or storage system may further drop the overall electricity generation cost at same penetration level.

This section created load and generation profiles by averaging time series over a day of month, it can lead to deviation in the results of related simulation performance, underestimate the PV variability and pump hydro storage dispatch role due to smoothing effects in the curves of demand and PV production. Future work will focus on different time series aggregation methods in selecting typical days for energy supply modelling, and compare techno-economical performances of PV integration in different regions of Japan.

Reference

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[3] METI, Power Generation Cost Analysis Working Group. Report on Analysis of Generation Costs, Etc. for Subcommittee on Long-term Energy Supply Demand Outlook. 2015.5. http://www.meti.go.jp/english/press/2015/pdf/0716_01b.pdf (accessed on 21 April 2018).

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Chapter 5

PERFORMANCE ANALYSIS OF DISTRIBUTED ENERGY SYSTEMS

CHAPTER FIVE: PERFORMANCE ANALYSIS OF DISTRIBUTED ENERGY SYSTEMS

Additionally to the requirements that are posed by the integration of RES, the buildings sector is facing a trend towards decentralized, more efficient technologies to cover the electrical or heating loads. With increasing share of efficient power technologies installed in electrical distribution grid, their integration to the public grid needs to be planned similar to the integration of renewable energy resources. Buildings can be part of the solution in these future smart energy grids, aggregated buildings will be both consumer and producer of energy (heat or electricity): these types of buildings are so called 'prosumers'. Buildings also offer on-site generation (rooftop PV, cogeneration system) and different storage potentials, either in the structure itself (thermal storage) or in individual units (hot water tank, battery). Finally, consumers can adjust their energy consumption to provide a flexible energy resource, generally based on incentive response.

In this chapter, techno-economic performances of advanced technologies including heat pump water heater, distributed on-site generators, such as PV, cogeneration system, and storage systems are investigated, potential effects of operation and management strategies in demand side are assessed. From the viewpoint of individual customers, the benefits in terms of reduced energy consumption related to high energy efficient appliances and shifted load pattern corresponding to specific tariff scheme. Overall impacts on the public grid are analyzed from bottom up approach, focus on grid load leveling and peak shave.

5.1 Introduction

Renewable production is hard to be scheduled since its generation highly depends on the nature. With increasing renewable penetration level, grid generation becomes less flexible to balance the flexible. Integrating an energy consumer's local energy supplies connects multiple energy networks in a decentralized way. Decentralized energy management or demand response is emerging as one of main approaches to resolve the network operation limits and to increase the flexibility of the system. As a result, the requirement of flexibility will not fall solely on plant side, but also part of flexibility requirement provided by demand side management. Smart meter, digital communication network and other advanced technologies enable the real-time information exchange between power supplier and customer. Private sector and local grid are expected to contribute to ensuring the efficient and sustainable use of natural resources and reducing carbon emissions. Furthermore, increasing incentive policy promotes the renewable technologies installed at home, such as rooftop PV generation, thermal storage, power battery cause residential load management to be more complicated. The potential and effects of demand side management will be quantifies and evaluated in the following, focusing on energy imbalance and peak load management.

5.1.1 Location scenario

Kitakyushu (33.5^{o} N, 130.5^{o} E), at the north of Kyushu island. According to the statistical weather data, the annual average temperature is 16.7 °C, the maximum daily solar radiation on horizontal surface reaches 27.4 MJ/m^2, summer period is relatively short and mostly cloudy, the winter is very cold, windy and partly cloudy and it is wet year round.

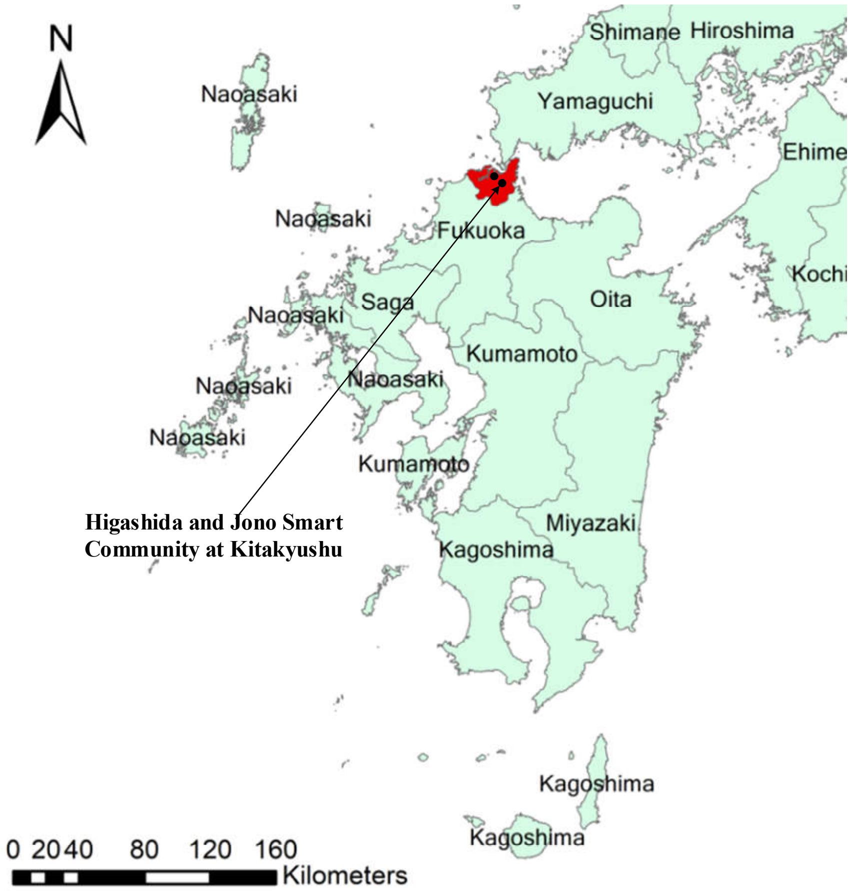


Fig.5-1. Location of Higashida and Jono Smart Community in Kitakyushu

Selected by the national government as an 'Eco-Model City', Kitakyushu has been taking on the challenge of being pioneers to process towards the creation of an environmentally friendly and low-carbon society through efforts such as promoting energy conservation, exploitation of local renewable resources and smart energy management. The real data of home efficient appliances and on-site generators are collected from Higashida Smart Community and Jono low carbon district at Kitakyushu as shown in Fig.5-1.

- Higashida Smart Community District covers around 120 hectares, consisting of residential, commercial, official and industrial components, features with 6000 employee, 10 million visitors per year, co-developed by the Fuji Electric system, GE, IBM and Nippon Steel. The project includes: real-time management of 70 companies and battery system, the hydrogen demonstration project, HEMS, BEMS and FEMS, dynamic price system, coexist verification between distributed power generators and public grid.

- Jono Low Carbon District demonstration project focuses on low-carbon initiatives that address CO_2 emissions from household. The extents of the advanced 'Zero-Carbon' Jono Town is composed of various residential daily energy-related activities. In regard to Jono area, various low-carbon technologies (Eco-cute, EVs, fuel cell, PV and battery) as well as measures are comprehensively employed in order to manage and advanced 'Zero-Carbon' residential district.

5.1.2 Motivation of demand side management

Residential consumers account for a major part of social power consumption, Fig.5-2illustrates the monthly residential power consumptions and ratios in Kyushu. Driven by the heating and air conditioning demand, the residential consumption shows great variations during the year and the fluctuation rises during air conditioning seasons.

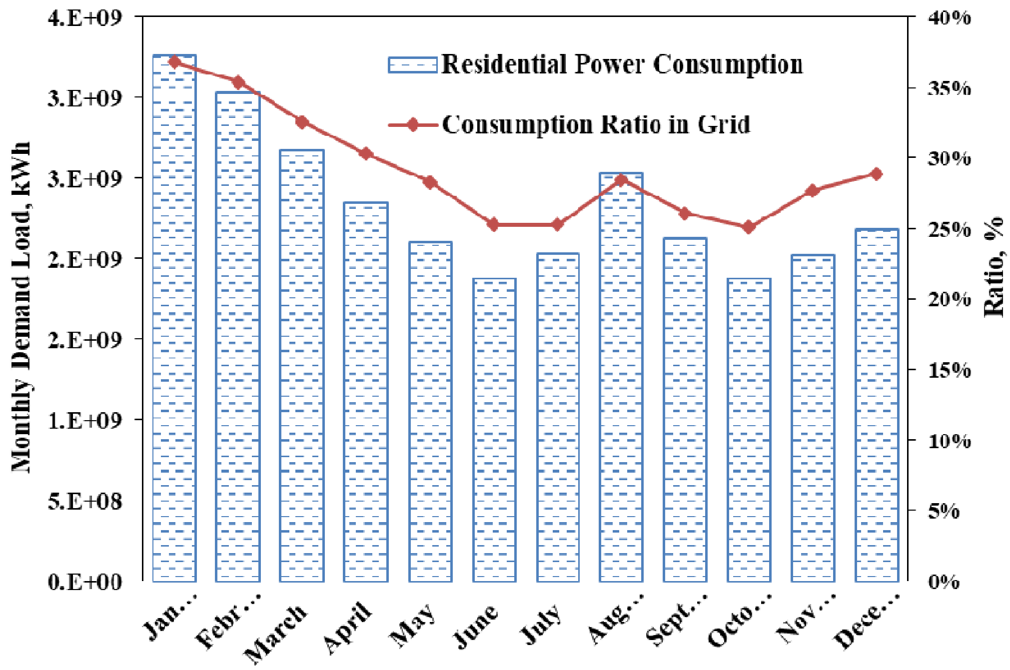


Fig.5-2. Monthly power consumption and ratio of residential sector during 2017, reference: Kyushu METI

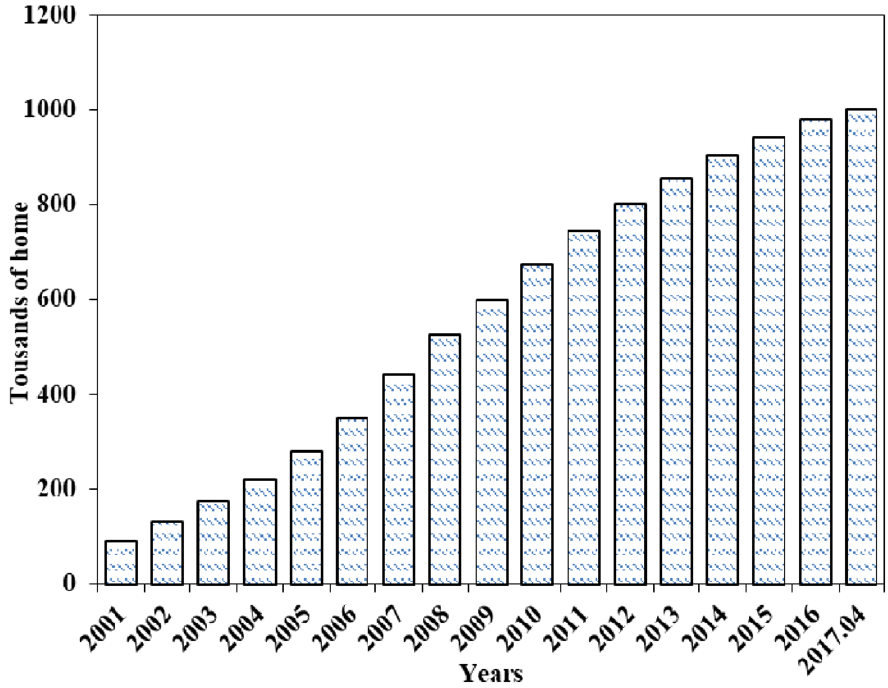


Fig.5-3. Number of all-electrification house in Kyushu, reference: Kyuden Electric Company

Renewable production is hard to be scheduled since its generation highly depends on the nature. With increasing renewable penetration level, grid generation becomes less flexible to balance the flexible demand load. Demand side management is seen as a resource of increasing the flexibility of the power system in terms of ability to balance the generation and demand. The spread of all-electric home has expanded due to the importance of safety and limiting the emission of gas, the cumulative number of all-electrification home has reached 100 million in Kyushu by April, 2017 as described in Fig.5-3 (7). Demand side flexibility aggregation becomes more important. Coordinate demand side management or control of home appliance under HEMS environment can reduce the overall customer's cost via shifting peak load during peak price period. For suppliers, benefits can be obtained through the investment replace of additional power generation facilities. As a result, the requirement of grid flexibility will not fall solely on plant side, but also part of flexibility requirement provided by demand side management. Aim of following parts will not only assess potential cost saving and environmental benefits for applications of high energy efficiency systems in private sector, but also evaluate public grid load leveling potential from bottom up approach.

5.2 Application of thermal storage system

Eco-cute generally refers to a heat pump water heater, utilizing natural refrigerant (carbon dioxide) that is environmentally safe. Its capability has been improved based on customer needs, making them more multifunctional with features such as the ability to support floor heating, and providing more space-saving models. Because it makes effective use of heat extracted from air, the system can generate heat energy more than 3 times greater than the input electrical energy. Fig.5-4 indicates the cumulative number of residential heat pump water system in Japan, it has experienced a rapid uptake over recent years.

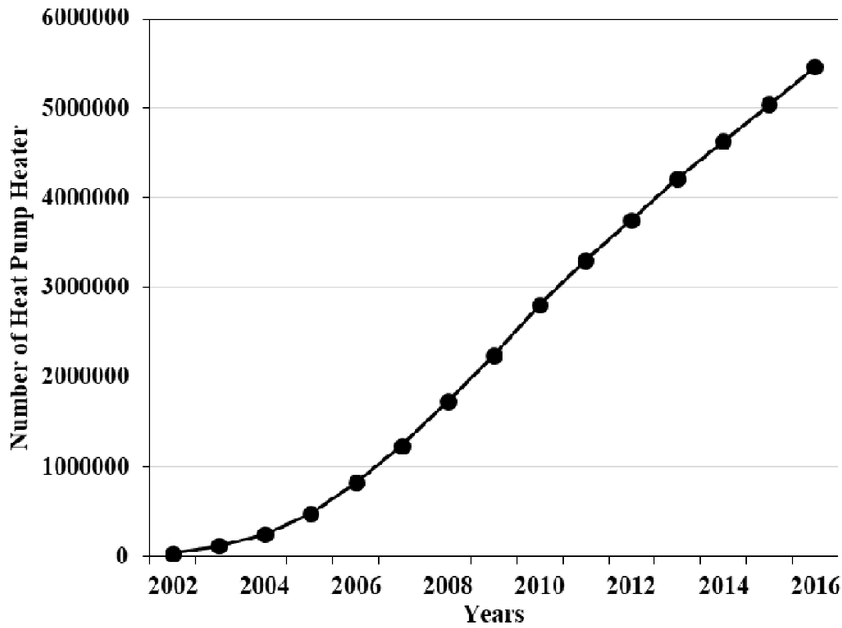


Fig.5-4. Cumulative number of heat pump water heater system in Japan

Heat pump takes place the role of conventional gas driven boiler in residential sector, energy saving potential highly depends on transform efficiency from electricity to heat, Fig.5-5 compares the primary energy consumption ratios between conventional thermal boiler (thermal efficiency 85%) and heat pump water heater systems. Primary energy consumption saving reaches 39% when overall COP of heat pump reaches 3.5, considering public electricity efficiency 40%.

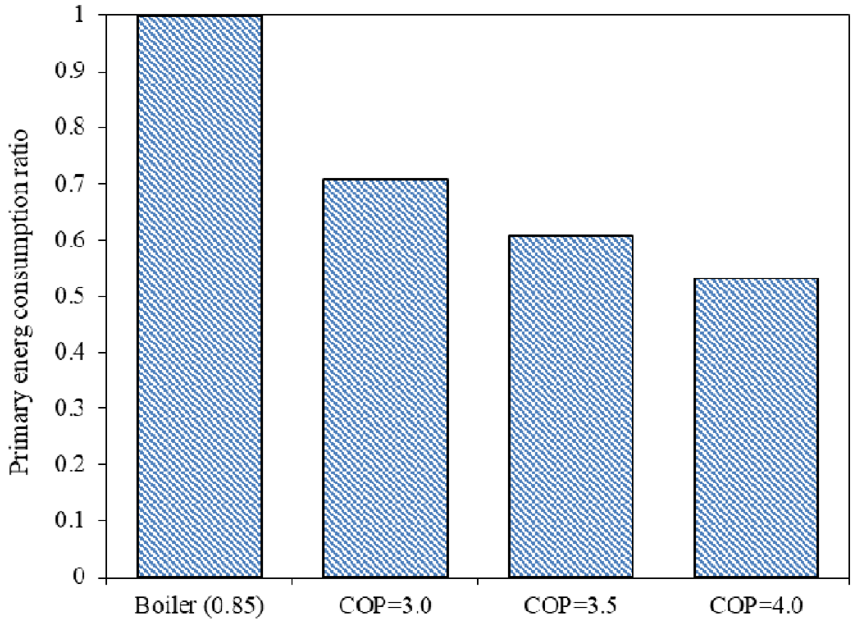


Fig.5-5. Primary energy consumption ratio of conventional thermal boiler and heat pump

Energy for hot water accounts for about 30% of total residential energy consumption in Japan, numerous heat pump water heaters in the residential sector had been developed with promotion of all-electrification household over recent years. The popularity of heat pumps is generally supported by (designed specific electricity tariff scheme) energy market and policy implications. Heat pump water heater is generally considered as useful appliances for environmental protection and load shifting. Thermal storage applications are integrated to shift the daily energy consumption pattern, and generally schedule the working time of heat pump water heater concentrates in lower pricing region (early morning and deep night) to provide potential economic benefits for customers.

Fig.5-6 illustrates the scheme of the residential heat pump water heater system, the local controller can receives the real time price single from the grid, switch on/off the heat pump, the work period of heat pump is optimized according to the price information from the grid. The produced heating will be stored in thermal tank, then released for daily later use.

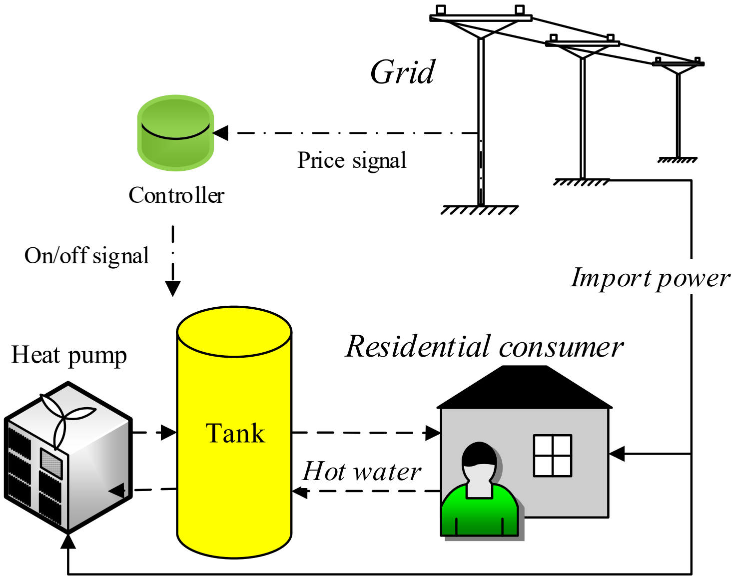


Fig.5-6. Scheme of residential household with heat pump water heater system

5.2.1 Load profile

Daily residential power loads are collected from 200 households in Higashida district at 1-hour interval. The selected households feature with all-electrification, heat pump water heater is responsible for daily hot water consumption. The daily loads for each month are obtained by average hourly load in months. Fig.5-7 presents the color-scale distribution of residential load in months equipped with heat pump water heater system. The daily energy consumption pattern has great relationship with the customer's habit, two daily peak periods of household load profiles mainly occur in the early morning and the evening. It also can obviously see that the baseload will increase during air conditioning seasons, early morning peak load driven by the utilization of heat pump water heater will obviously increase, due to the production of hot water that mainly lasts from 0:00 am to 6:00 am with cheap electricity price according to time of use pricing scheme. Fig.5-8 illustrates the variations of daily average residential power consumption in months, vary from minimum 14.1kWh/day to maximum 25.7kWh/day.

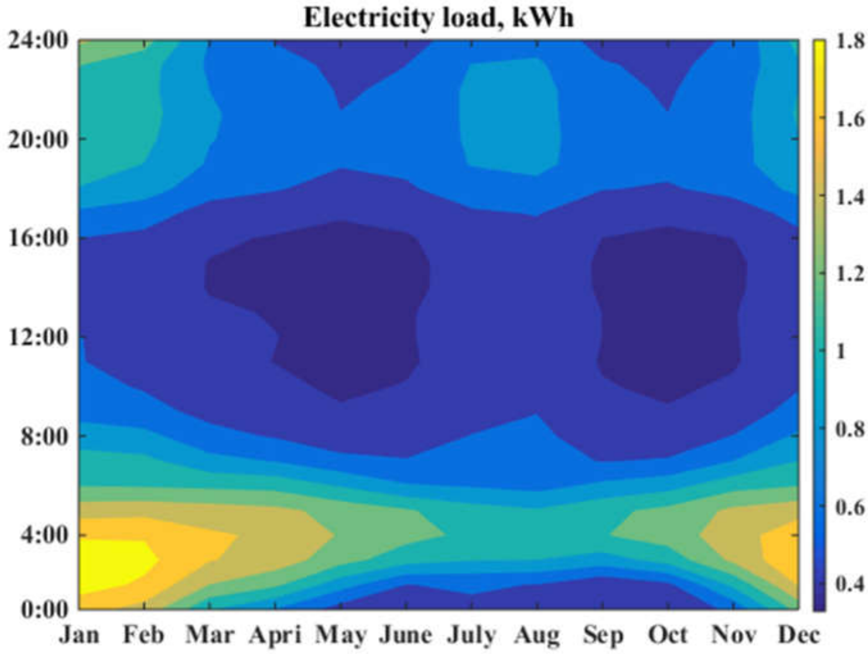


Fig.5-7. Load color scale distribution of residential household equipped with Eco-cute

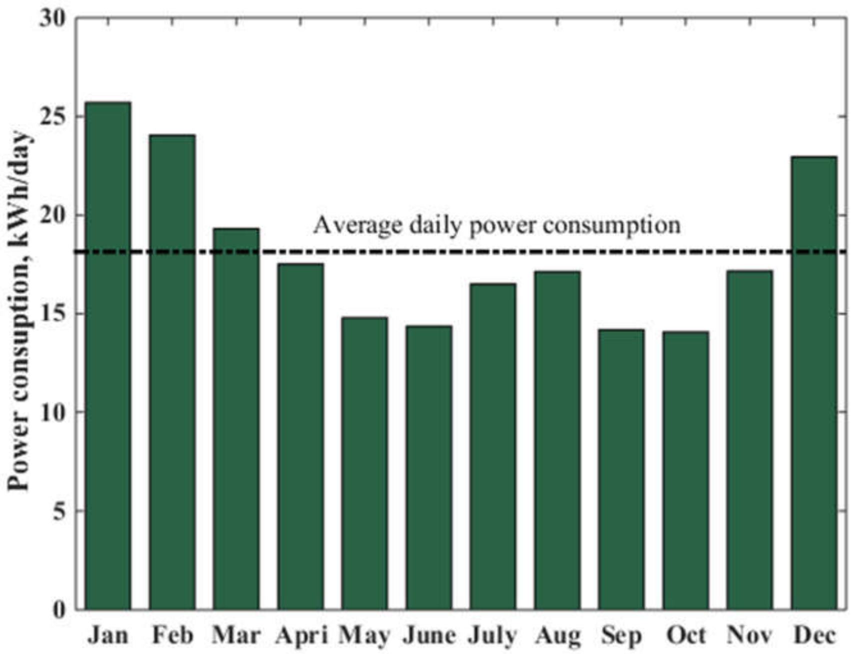


Fig.5-8. Average daily load power consumption in each month

5.2.2 Performance analysis

In order to investigate the detail consumption composition and seasonal variations, the power consumptions of selected households were collected over a week, including detail consumption of heat pump, light, air condition and others. Data are collected at minute interval through smart meter, Fig.5-9&5-10&5-11 illustrate the information of residential load in different season periods, it can clearly see that daily power consumptions rise obviously during winter period, driven by the increasing heating demand and air conditioning demand.

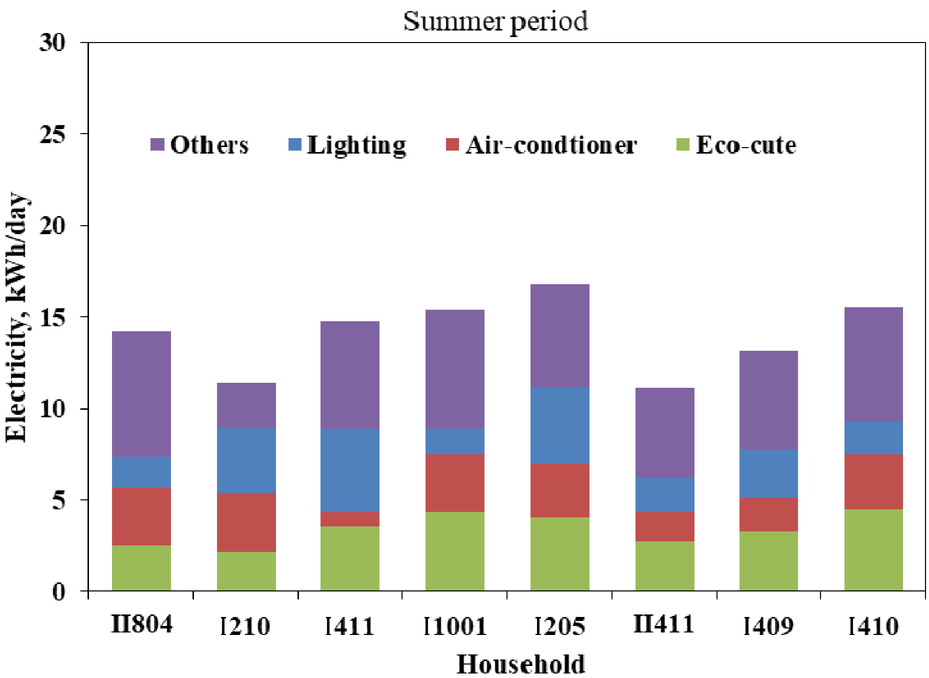


Fig.5-9. Information of residential power load in summer

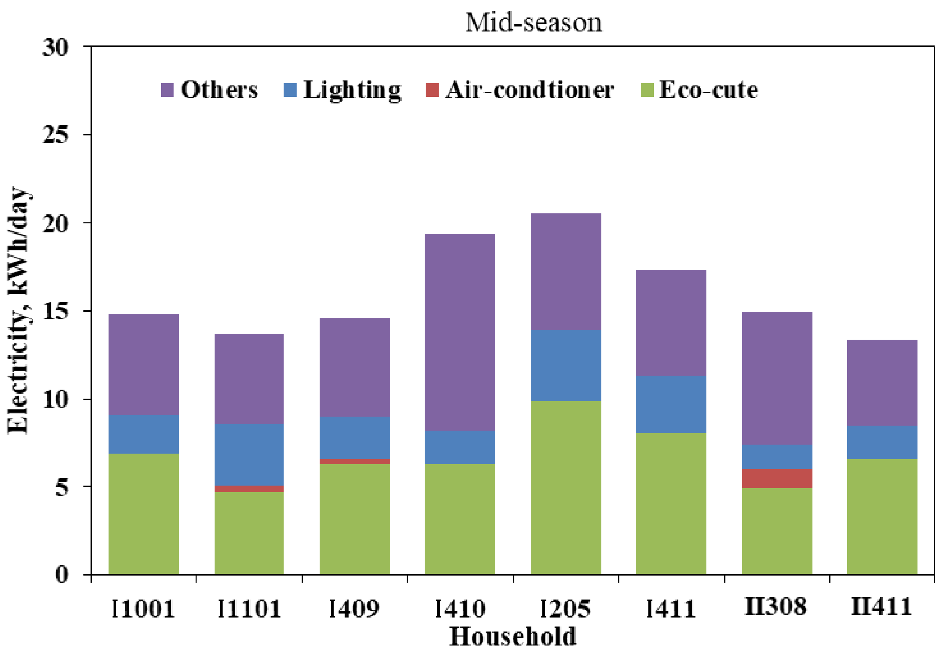


Fig.5-10. Information of residential power load in mid-season

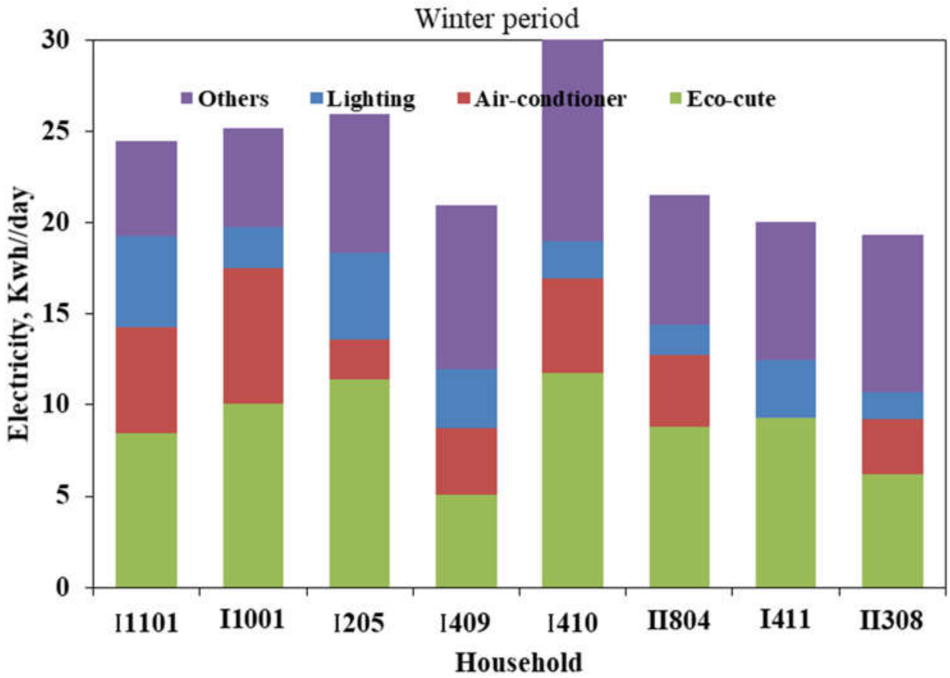


Fig.5-11. Information of residential power load in winter

Fig.5-12 illustrates the distributions of monitored heat pump water heater power consumption ratios of daily load in different seasons, generally range from 20%~45%. Increasing heating demand, drop in value of COP and rising energy loss jointly lead the increases of heat pump power consumption during winter period.

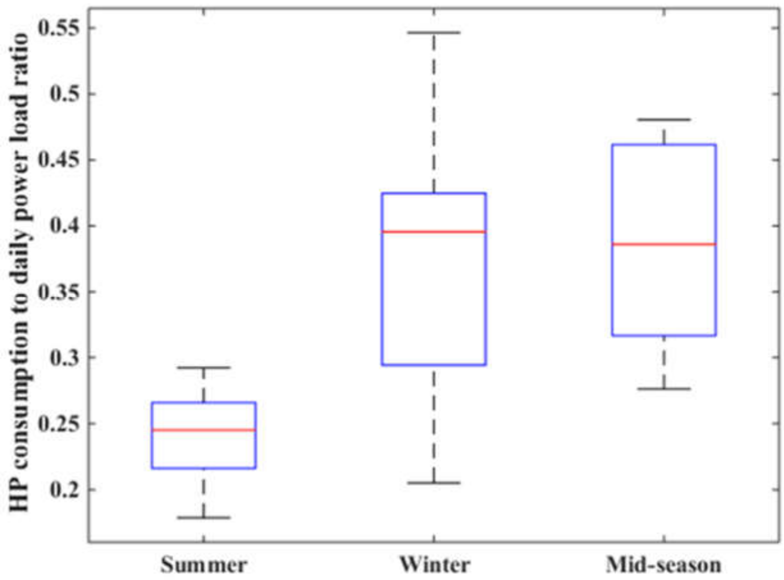


Fig.5-12. Distribution of power consumption of heat pump water heater to daily power load ratio

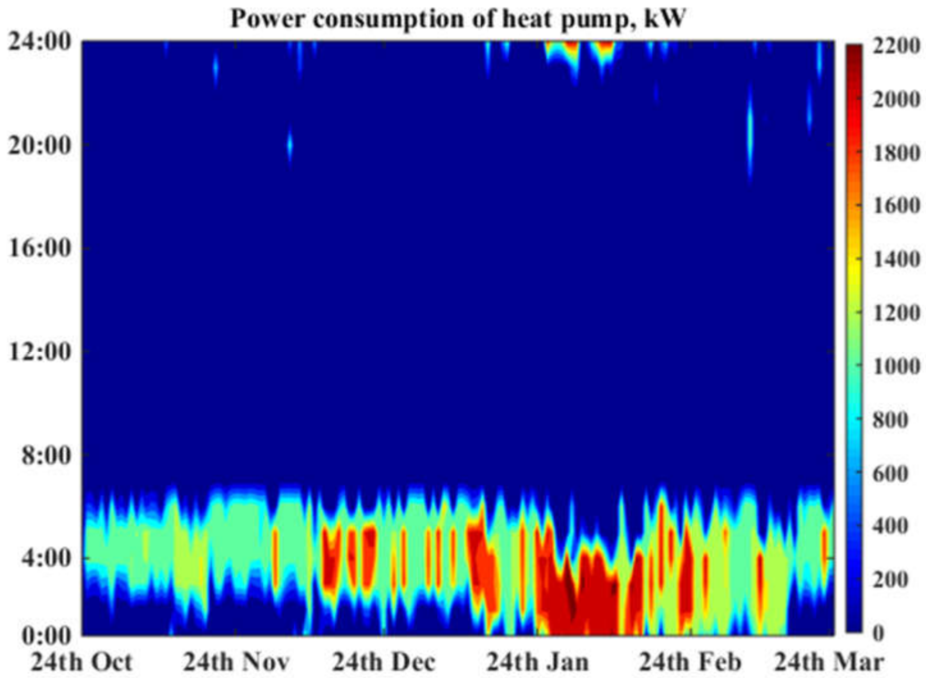


Fig.5-13. Color scale distribution of power consumption of heat pump sector in a typical residential house

Fig.5-13 presents the color scale distributions of power consumption of heat pump water heater in a typical residential household. Working period of heat pump mainly lasts from 0:00 to 7:00 am, locates in the valley period of demand load. Operating time become shorter with daily decreasing heating demand, heat pump water heater system shows higher power consumption density in winter, attributed to the higher heating demand and lower generating efficiency under low ambient temperature. Heat pump water heater tends to operate earlier in winter time to meet the daily heating load, which may be highly dependent on activity based load.

5.2.3 Result and evaluation

Heat pump replaces the role of gas driven heat water system, shifts heating demand into early morning or evening period. In order to analyzes the potential economic and environmental benefits, the technical and economic parameters are illustrated in Table 5-1.

Table 5-1. Cost and technical input parameters [1-3]

Variables	Value
Annual COP of heat pump	3.4
Daily heat pump power consumption	5.6 kWh (30% of average daily load)
Cost of heat pump	8000$ (4.5 kW, 370L tank)
Lifespan of heat pump	12 years
Valley price of electricity	0.11$/kWh
Gas pricing	1.86$/Nm^3
Lower Heating Value	45 MJ/Nm^3
CO_2 emission of natural gas	2.29 kg/Nm^3
CO_2 emission of electricity	0.483 kg/kWh
Thermal efficiency of gas boiler	85%

Heat pump replaces the role of gas driven heat water system, shifts heating demand into early morning or evening period. In order to analyzes the potential economic and environmental benefits, the technical and economic parameters are illustrated in Table 5-1.

Price scheme described in Fig.5-14 is suitable for heat pump users, time of use tariff structure that 0.22 $/kWh in daytime lasts from 8:00 to 22:00, 0.11$/kWh from 23:00 to 7:00 (3). It encourages customers to schedule their daily energy consumption according to time of use scheme for overall cost reduction on daily basis.

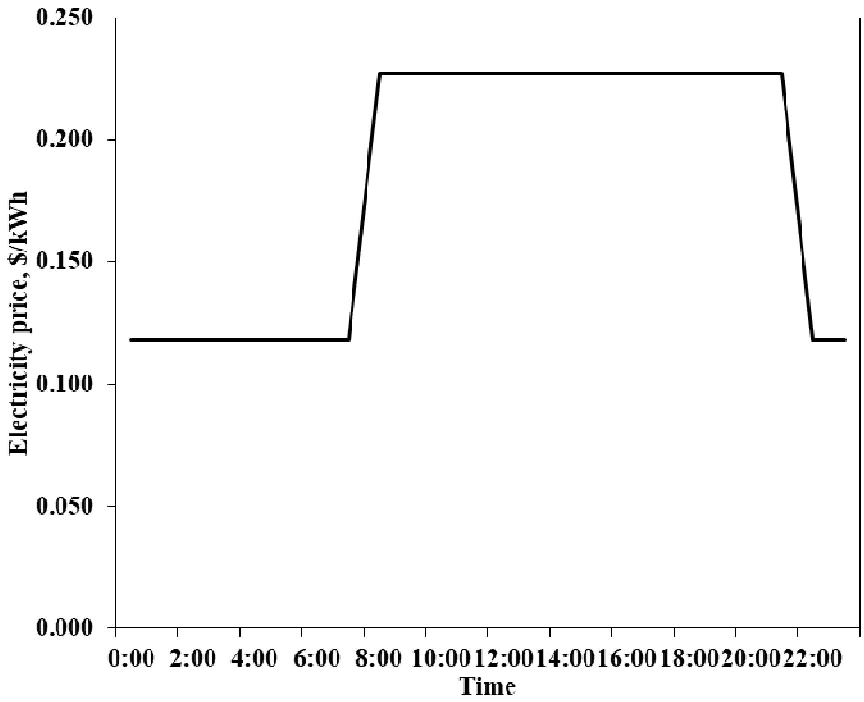


Fig.5-14. Time of use tariff structure, reference: Kyuden Power Company

Equivalent consumed gas volume can be calculated as following:

$$V = \frac{P_{HP} \bullet COP}{LHV \bullet \eta_{heat}} \quad \text{Eq 5-1}$$

Where, P_{HP} refers to the average daily power consumption of heat pump, LHV is lower heat value of natural gas, and η_{heat} presents general efficiency of conventional heating system, V is equivalent consumed gas volume to produce same hot water. The detail values of parameter can be found in Table 5-1.

$$NPV = \sum_{j=1}^{n} R_j \cdot (1+i)^{-j} - C_0 \quad \text{Eq 5-2}$$

As given in Eq 5-2, the cash inflows (R_j) refers to the annual net profit for the generic year j=[1,2,…,n], from the price differences between gas and electricity consumption, C_0 presents the installation cost, choosing the annual discount rate i equals to 4.0%, set average annual profit 1062$/year, meanwhile achieved CO_2 reduction 547 kg per year. Fig.5-15 presents the net present value of heat pump water heater system within lifespan 12 years. Results indicate that customer can achieve net benefit by 11^{th} year after implementing the heat pump water heating system.

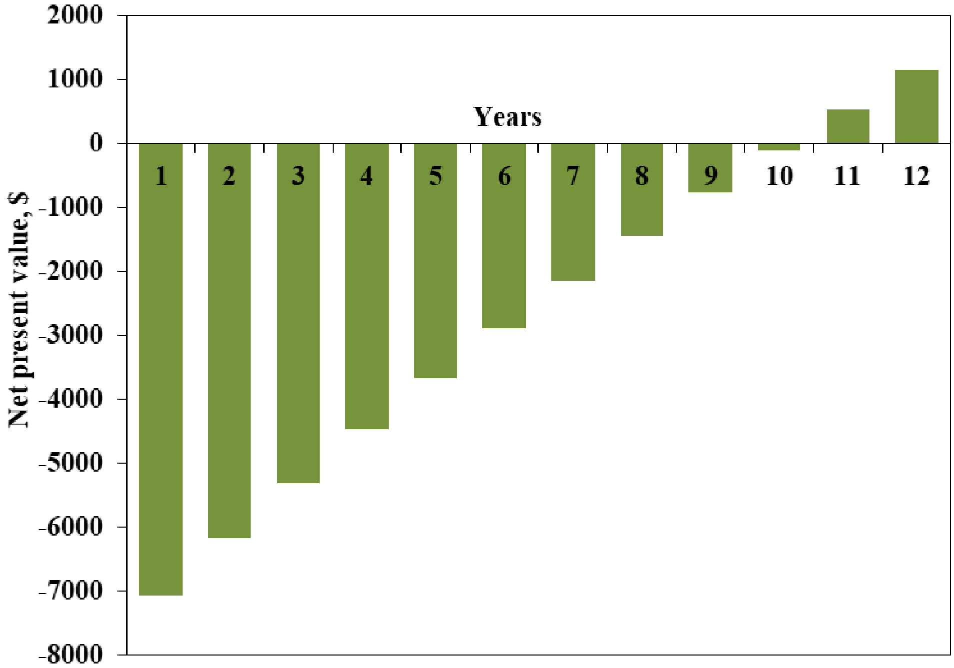


Fig.5-15. Net present value of heat pump water heater system

5.3 Application of power storage system

5.3.1 Objective

For energy storage application to stabilize the power system, Japanese government official roadmap set a target of reducing the cost by 90% until 2030 from the current technical level. Residential battery market in Japan falls into two main categories, increasing local energy self-consumption and public grid parity. The existing subsidy driven the uptake of Li-ion batteries in residential sector [4]. As its production scale has increased and manufacturers have developed more cost-effective methods, production cost of Li-ion battery also has come down significantly. First mass-market EVs were introduced in 2010, their battery packs cost an estimated $1,000 per kilowatt-hour (kWh), and it is expected to reach the 125-150 $/kWh, as shown in Fg.5-16. If battery costs continue to decline as EV production increases, it will make EV competitive with conventional gasoline vehicles.

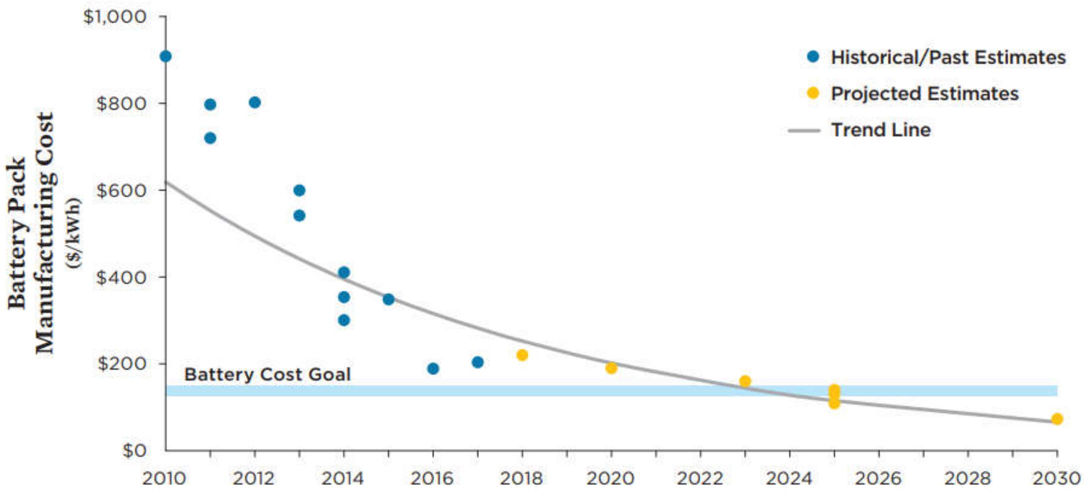


Fig.5-16. Cost scenario of Li-ion battery, reference: Global EV outlook 2017

The Japan government aims to capture 50 to 70% of next-generation vehicles to total new car sales by 2030, electric vehicle plug-in hybrid vehicle is expect to account of 20-30% of diffusion target. Panasonic develops the smart HEMS linked to cloud computing service, its function supports EV charging facilities and smart meters equipped with communication functions, making them useful as electricity supplies in communities. As EV penetration increases, it is expected to contribute to peak shift as part of energy management system, the EVs project is demonstrated in Jono low carbon district.

Grid utility has been making efforts by giving incentives to vehicle to home (V2H) customers to modify their power consumption. Controller in customer side can receive the price signal, scheduling strategy enables EV charge during the grid valley period and discharge power to home at night, typical accomplished in HEMS environment. Fig.5-17 illustrates the scheme of EV application in residential sector. The plug-in electrical vehicle not only receives charge from the grid to power the vehicle, but also provides backup power to the household. EV provides two-way flow from grid and to home, functioning electric power grid for peak shaving or enhancing local energy security. Potential opportunity to manage increasing electricity costs and demand spikes is the utilization of EVs to act as an aggregated energy store, providing peak shaving or demand shifting to both local buildings and to the power system when demand is high. Electrical vehicle for residential demand response could bring potential benefits to both of power supply and demand side, supporting peak reduction from aggregated form and reducing customer energy cost under time of use tariff scheme. This section will mainly analyze the techno-economic performance of residential EV system (V2H),

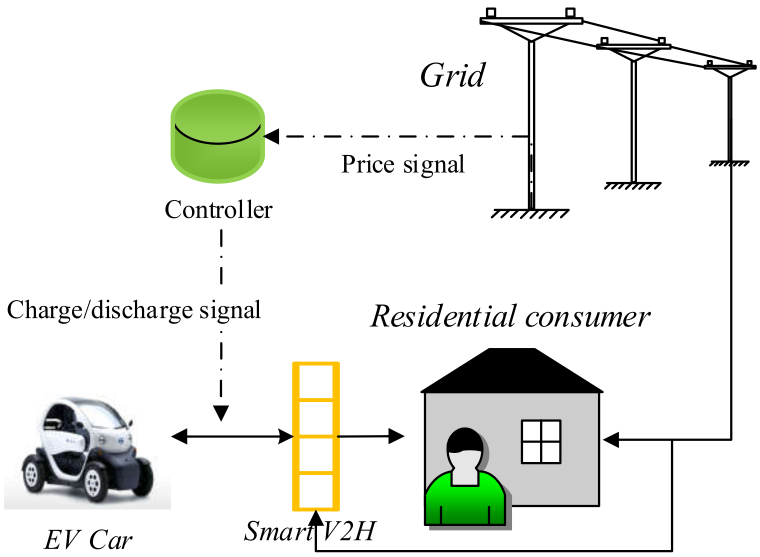


Fig. 5-17. Scheme of residential household with smart V2G system

5.3.2 Application scenario

Residential energy data collected from the social demonstration project in Jono, Kitakyushu. Fig.5-18 describes the color-scale distributions of power flows from residential EV system, half year period composed of 183 days. Daily power flows of the EV highly depends on the electrical usage, i,e. when, where and how much power is charged. It can clearly seen that plug in condition mainly concentrates in midnight from 23:30 to 3:00, maximum charging ability reaches 2.5 kW, EV discharging domain generally occurs after work that lasts from 17:00 and 23:00, this actually coincides with grid valley and peak demand. EV uptake could lead a valley increase of 2.5 kW in evening, and provide around 1.8 kW peak reduction limited to residential load, daily charge power is around 8.5 kWh, around 41% of charged power will be released to home electricity consumption, it means that around half of stored power will be used to replace the oil consumption of the EV car.

The color distributions of power flows from EV confirm that expand use of EVs could be scheduled to shape the grid load from aggregated perspective.

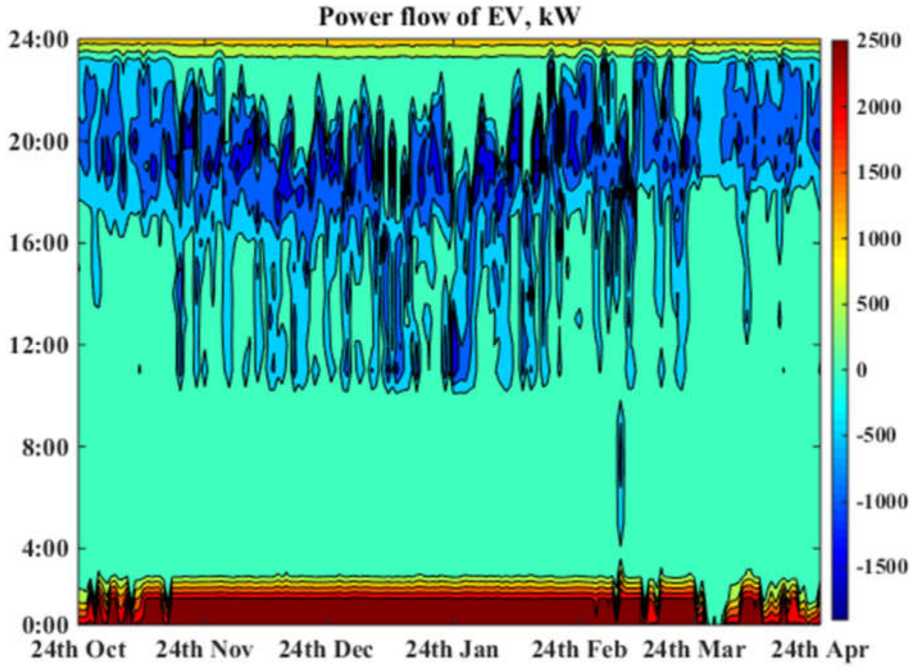


Fig.5-18. Color-scale distribution of power flows in V2H system

5.3.3 Analysis and results

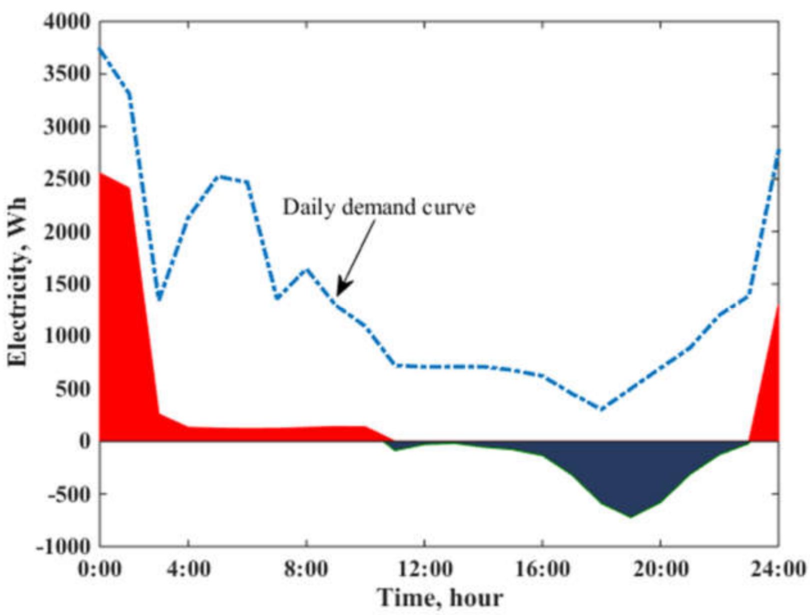


Fig.5-19. Average load profile and power flows of EV

Fig.5-19 presents the daily average load profile and power flows of EV over 183 days, lasts from

24th October to 24th April. The EV will charge into until full saturated condition in night or early morning period, then it comes into discharging process during night peak period, covering the night peak load, generally in absence of on-site renewable generation. Estimated powers come from EV system can cover average 9.2% of residential daily load. Charge process rises the load in night period, discharging ability is limited the simultaneously daily load profile with consideration of the real-time load balance.

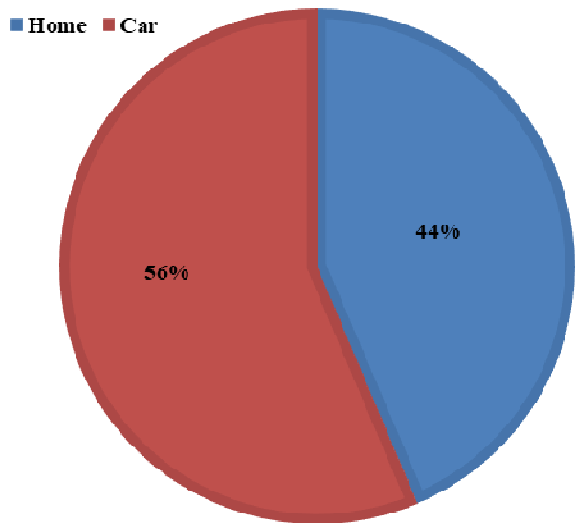


Fig.5-20. Power consumption of EV by household and car

As shown in Fig.5-20, it can estimate that more than half of charged energy is used to replace the consumption of gasoline, and 44% percentage of stored energy is released for residential energy related activities. In order to analyze the economic and environmental benefits of EV. Table 5-2 presents the cost and technical parameters of EV car. Fig.5-21 shows the residential average daily profit structure with add of EV, composed of electricity cost save through discharging at higher price period and fuel cost saving of the car. It brings a promising benefit via replacing the gasoline fuel of the car. Meanwhile, it achieves carbon emission reduction through transform of fuel to electricity, CO_2 5.1 kg/day.

Table 5-2. Cost and technical input parameters of EV [6]

Oil Pricing	1.18 $/L
EV car consumption	9.5 km/kWh (electricity), 12.5km/L (Oil)
Charge efficiency	90%
Discharge efficiency	90%
Gasoline emission	2.32kg/L
Valley price of electricity	0.11$/kWh
EV battery cost	600 $/kWh
CO_2 emission of electricity	0.483 kg/kWh

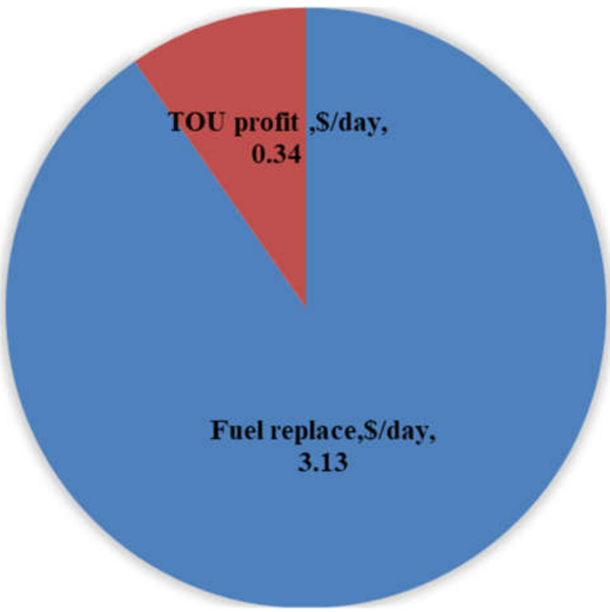


Fig.5-21. Daily average profit structure of EV objective

$$NPV = \sum_{j=1}^{n} R_j^1 \cdot (1+i)^{-j} - C_0^1 \quad \text{Eq 5-3}$$

In order to investigate the economic feasibility of EV system under current energy market, NPV of EV is calculated based on cost parameters in Table 5-2. As described in Eq 5-3, the cash inflows (R_j^1) refers to the annual net profit of EV for the generic year j=[1,2,…,n], from the replace of part gasoline and battery dispatch, C_0^1 presents the installation cost, choosing the annual discount rate i equals to 4.0%. Fig.5-22 illustrates the net present value of EV system of 10 years within the lifespan of battery. Cumulative profit is able to cover the capital cost of battery storage, which is attributed to the price differences between gasoline and electricity.

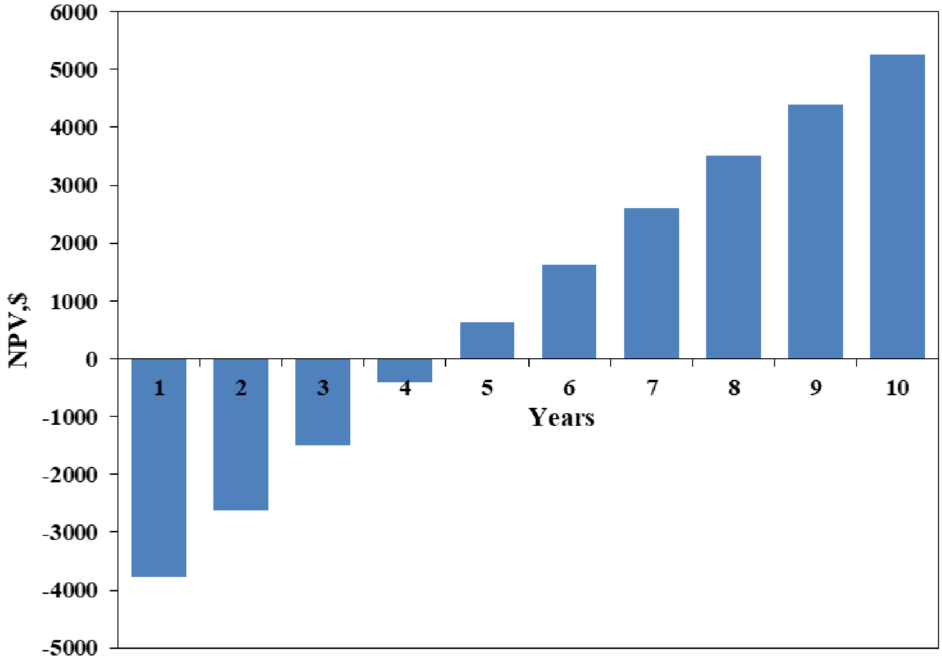


Fig.5-22. Net present value of EV system

5.4 Application of PV-battery model

After the implementation of feed in tariff and relative incentive policies, large amount of solar generation fed into the public grid from the distributed private sector. Large ratio of the installed solar PV system are in distributed form that connected in low-voltage. Meanwhile, the feed in tariff of PV generation is experiencing a decreasing trend over recent years. Stricter feed-in limitation is expected in future, the feed in tariff for the grid-connected residential PV system has dropped from 0.38 $/kWh in 2011 to 0.22 $/kWh in 2018 as illustrated in Fig.5-23 (5).

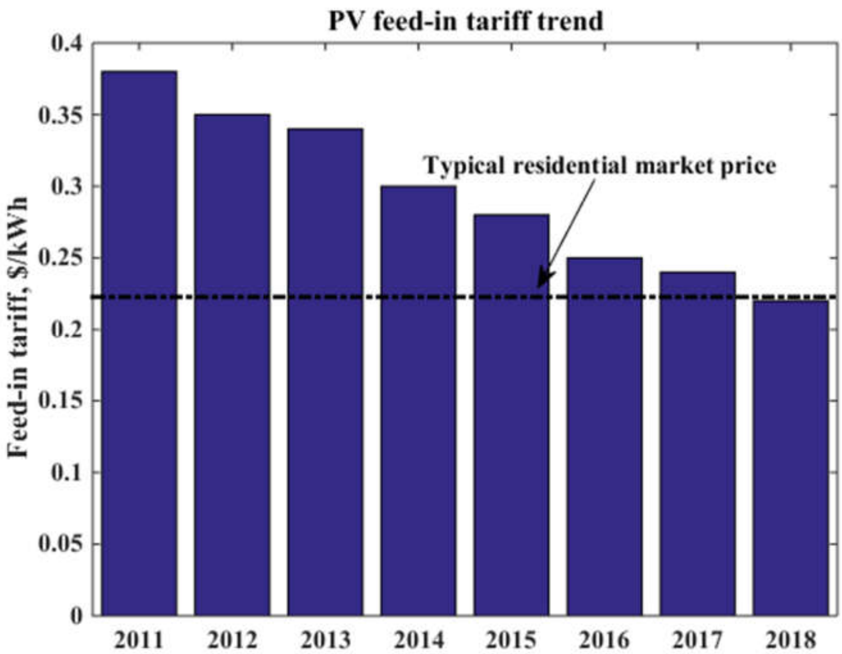


Fig.5-23. Feed-in tariff trend in Kyushu

The distributed PV battery from is expected to reduce the customer's electricity bill and participate more in grid load optimization through optimal management strategies in aggregated level. In addition, there is a significant battery installation market potential from bottom up perspective, accompanied by the falling price of battery in coming years. This section will investigate the techno-economic performances of PV and battery application in residential sector.

5.4.1 Data sources

This electricity loads composed of approximately 200 residential households in Kitakyushu district, at the north of Kyushu island, and local climate information were obtained from on-site physical meters at 30-min interval over one year. The daily average curves of residential load and solar irradiation in each month are shown in Fig.5-24. The daily peak electricity loads of the household mainly occur in the early morning and the evening, which is a common habit in Japan households.

The solar irradiation is rich in transition season or summer month, it generally experiences its maximum value in the middle of the daytime.

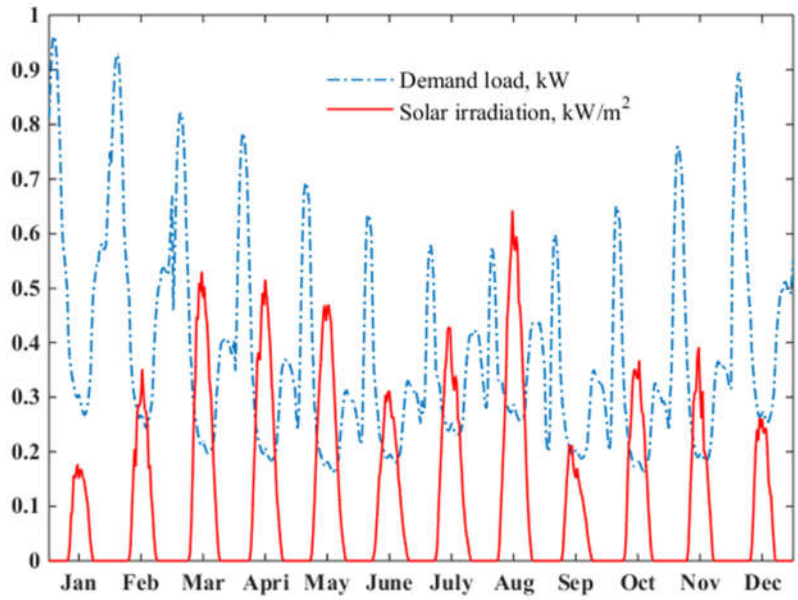


Fig.5-24. Profiles of the residential electricity load and solar irradiation

Local solar irradiance and temperature data can be used to determine PV power generation, the output from PV can be calculated by the following equation:

$$P_{PV} = \eta_{PV} S_\alpha I_\alpha (1 - 0.005(T_o - 25)) \quad \text{Eq 5-4}$$

Where η_{PV} is the yearly average conversion efficiency of solar cell array, 16.0%, S_a is the array area m^2, I_α is the solar irradiation on an inclined surface, kW/m^2, T_o is the outdoor air temperature, ^{o}C. The angle of incidence of the solar array panel is considered as 30 degrees.

5.4.2 Dispatch strategy

Fig.5-25 illustrates the schematic layout and energy flows of the grid-connected residential PV-battery system, consists of a DC-coupled PV and battery system. The battery storage unit will be used to transfer the power in time due to the low correlation between PV power generation and residential load profiles. Power generation from PV system has priority in meeting the local household electricity demand P4, excess generation can be directly sold to the public grid P5 or stored in battery system P3. Depending on the application scenario, the battery as a balancing tool is charged while the considerably surplus PV generated, maximizing self-consumption level. Then the battery will come into discharge condition to provide additional power P1 to reduce the imported power from the public grid. The public grid can supply power P2 to cover demand over the period when the PV generation is insufficient or unavailable. Considering the features of grid and customer load profiles, the battery can be a means to raise PV self-consumption ratio, meanwhile shift the net grid load through reducing the reverse flow and discharging corresponding to peak pressure in aggregated level.

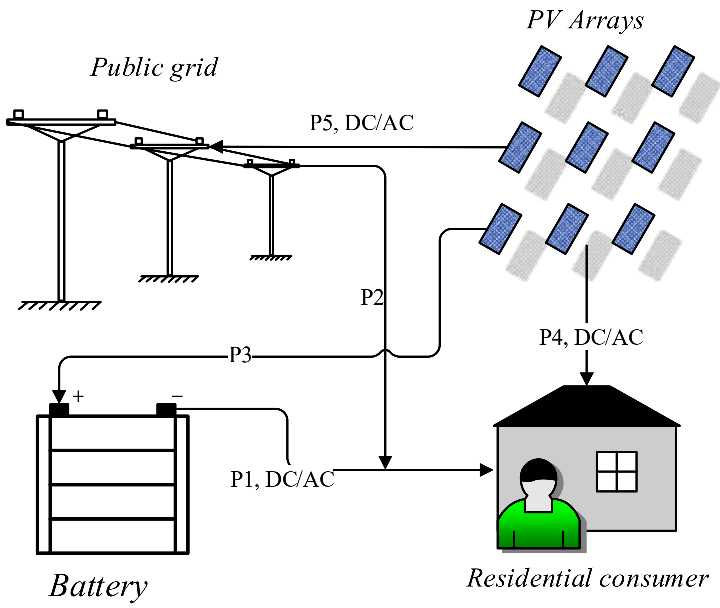


Fig.5-25. Layout of the grid-connected residential PV-battery system

5.4.3 Simulation model

The integration potential and feasibility performances of the residential PV system are limited to times with simultaneous generation and load profiles. Better correlation between the generation and load profiles will provide a more suitable scenario for increasing the local PV capacity. The direct feed-in ratio and self-sufficiency of PV are usually used as the main evaluating indicators for the residential PV system. Feed-in ratio is defined to be the amount ratio between the consumed PV energy and the amount of total PV production, self-sufficiency can be calculated as the ratio of the feed-in PV energy to the residential demand. The self-consumption ratio is limited by the smallest value of either the PV generation $P_{pv}(t)$ or residential electricity load $L(t)$ and is given by:

$$S(t) = \min\{P_{pv}(t), L_{re}(t)\} \quad \text{Eq 5-5}$$

The PV electricity self-consumption rate is defined as on-site consumed PV power to the whole PV generation:

$$\varphi_{sc} = \frac{\int_{t=t1}^{t2} S(t)dt}{\int_{t=t1}^{t2} P_{pv}(t)dt} \quad \text{Eq 5-6}$$

Replacing the $P_{pv}(t)$ with the load $L(t)$, the degree of self-sufficiency can be expressed as:

$$\varphi_{ss} = \frac{\int_{t=t1}^{t2} S(t)dt}{\int_{t=t1}^{t2} L(t)dt} \quad \text{Eq 5-7}$$

In 30-min resolution, using annual real measurement data to smooth the average monthly demand curve and simulated PV generation profile, Fig.5-26 shows the simulated self-consumption rate and degree of self-sufficiency of the residential PV system without storage system. When we vary the installed capacity of PV array from 1.0 kW_p to 7.0 kW_p, the self-consumption rate will decrease with larger PV system sizes due to excess generation cannot be consumed locally, and the decreasing rate is obvious at initial stage. In contrast, self-sufficiency level will rise with larger PV system sizes, then the growth rate shows a slowdown and becomes incrementally saturated. Nowadays, most common capacity of the private house PV system in Japan is mainly between 4.0 kW_p to 5.5 kW_p, due to the limited roof area and limited weigh bearing capacity of the building. As illustrated in Fig.5-26, capacity of PV in this range, self-consumption ratio is relatively low and the self-sufficiency is close to its maximum level, indicating that large ratio of PV generation will has to be fed into the grid without battery storage system.

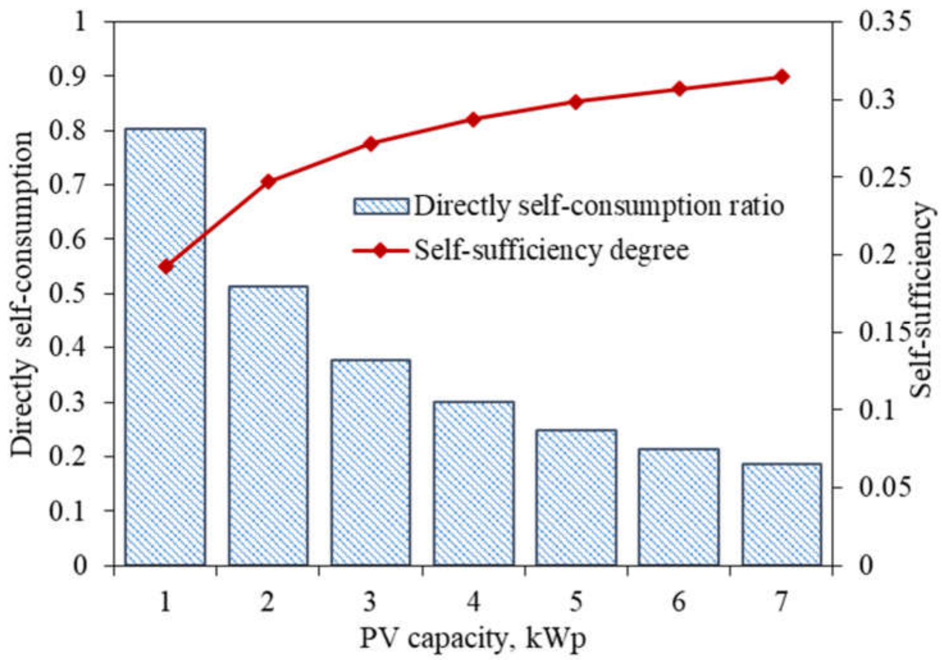


Fig.5-26. Self-consumption and self-sufficiency rates for residential household as a function of the 5.0 kWp PV size, without battery storage system

Fig.5-27 illustrates the detail power flows of the grid-connected residential PV system with installed PV panels 5.0 kW_p capacity. PV generation can greatly excess the electricity load during the transition seasons or summer month. It means that part of the PV generation has to be fed into grid or suppressed without storage unit.

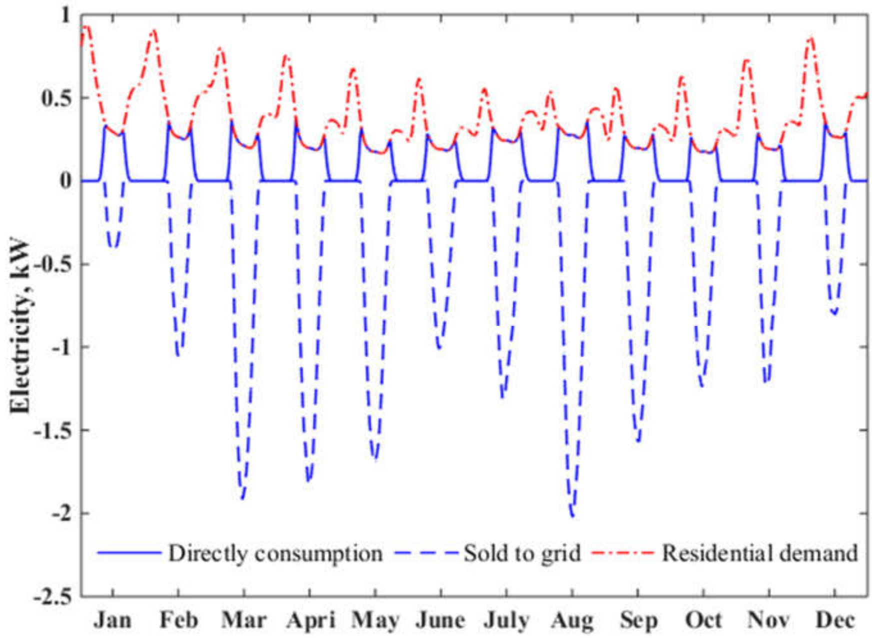


Fig.5-27. Power flows of the grid-connected residential PV system, 5.0 kW$_P$ capacity without battery storage

In the residential PV battery model, the battery storage can be optimized to maximize the self-consumption rate and match the generation and consumption profiles. The battery will be charged until full when the PV generation is over the electricity demand. Then the battery is optimized to release the power when the PV generation is unable to cover the residential load. The model aims at minimizing the amount of electricity bought from the public grid:

$$\min \sum_{t=t1}^{t2} P2_t \quad \text{Eq 5-8}$$

To ensure the electricity demand of the consumer at each time step, the load balance equation is subject to:

$$P1_t + P2_t + PV_t = load_t + P5_t + P3_t \quad \text{Eq 5-9}$$

Where, PV_t is the generation of the PV system and $load_t$ is the household electricity load at time t. Regarding the battery lifetime, the storage system should operate within its nominal range. The generation capacity of the storage battery is limited to maximum charging/discharging rates, simultaneous PV generation and load profiles:

$$P3_t = \min(\beta_1 \cdot Cap_B, \max(PV_t - load_t, 0)) \quad \text{Eq 5-10}$$

$$P1_t = \min(load_t, \beta_2 \cdot Cap_B) \quad \text{Eq 5-11}$$

β_1 (0.2), β_2 (0.15) are the ratios between maximum charging/discharging rates and battery capacity, Cap_B is the nominal capacity of the battery. Stored energy state of the battery at time step t can be calculated:

$$E_B(t) = E_B(0) - \sum_{t=1}^{N} P1_t / \eta_1 + \eta_2 \sum_{t=1}^{N} P3_t \quad \text{Eq 5-12}$$

η_1 and η_2 are battery discharging (90%) and charging (95%) efficiency respectively. During the operational cycle of the battery, the whole amount of charge and discharge power should be almost equal, the states of battery as limit index are described as:

$$E_B^{\min} \le E_B(t) \le E_B^{\max} \quad \text{Eq 5-13}$$

Deep charge of the battery is unfavorable, in order to preserve the battery lifetime, the minimum state of charge $E_B^{\min}$ is set to 20%, the maximum $E_B^{\max}$ is equal to 95% of the battery nominal capacity in the simulation.

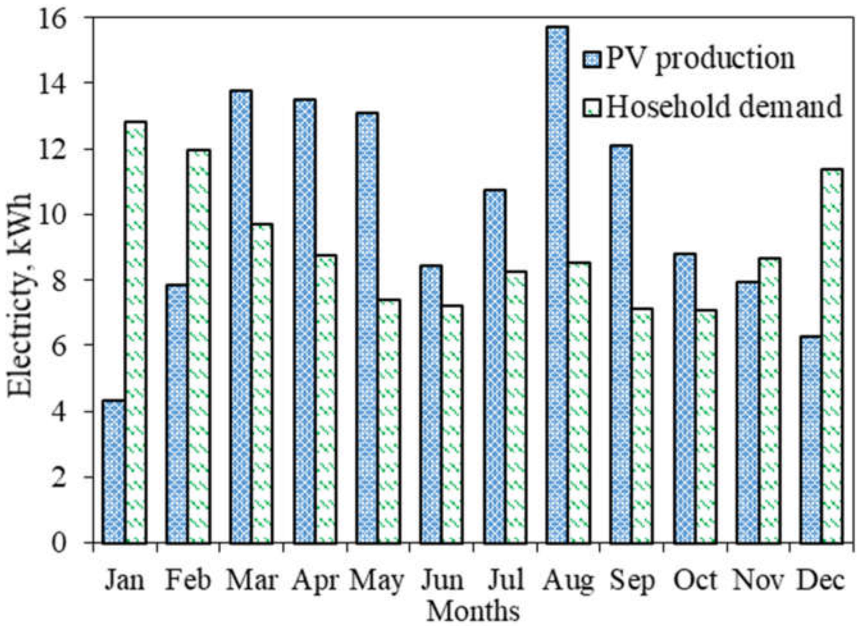


Fig.5-28. Average daily PV generation (5.0 kW$_p$ capacity) and household electricity consumption of each month

The daily average PV 5.0 kW$_p$ production and electricity demand in each month are illustrated in

Fig.5-28, it can clearly see that the PV system experiences its maximum generating capacity in August when the solar irradiance is relatively high, its power generation has considerably excess the household demand level. The household electricity load presents the largest value in winter that there is a high electricity demand associated with the operation of electricity driven heater and air conditioning equipment. However, the PV productions show relatively small value. It is worth noting, due to the local rainy climate condition, PV system shows a relatively low generation capacity in June.

5.4.4 Analysis and results

The self-consumption rate and self-sufficiency degree of the household PV system for each month are simulated corresponding to the above mentioned profiles of average daily PV generation and household electricity load. Fig.5-29 shows the effects of relative battery size on PV self-supply performances (PV with 5.0 kW_p capacity), self-consumed energy rises with the uptake of battery, self-sufficiency ratio will increase hence the load remain remains constant. Self-consumption level increases obviously with larger battery sizes at initial stage, because excess PV generation can be stored for later use, and the effect tends to become less or even disappear at higher relative battery capacity. Table 5-3 lists the detail simulated self-consumption rates over one year when the relative sizes of the battery increases from 0.0 to 2.0 (0 kWh to 10.0 kWh). It is worth noting that the self-consumption rates of the PV system with increasing battery size exhibit great variations across the months, the self-consumption rates feature with high initial value in January and December, large ratio of PV generation can be directly consumed in the private household, excess generation can be absorbed by adding a battery unit with relatively small capacity. However, directly self-consumption rates show relatively small values in transition seasons and August, indicating that the customer has to sell considerable excess generation into the grid without storage dispatch. And it generally needs relatively large battery size to increase the self-consumption to high level, the self-consumption ratios of all months come into saturated condition when increase the relative battery size to 1.8.

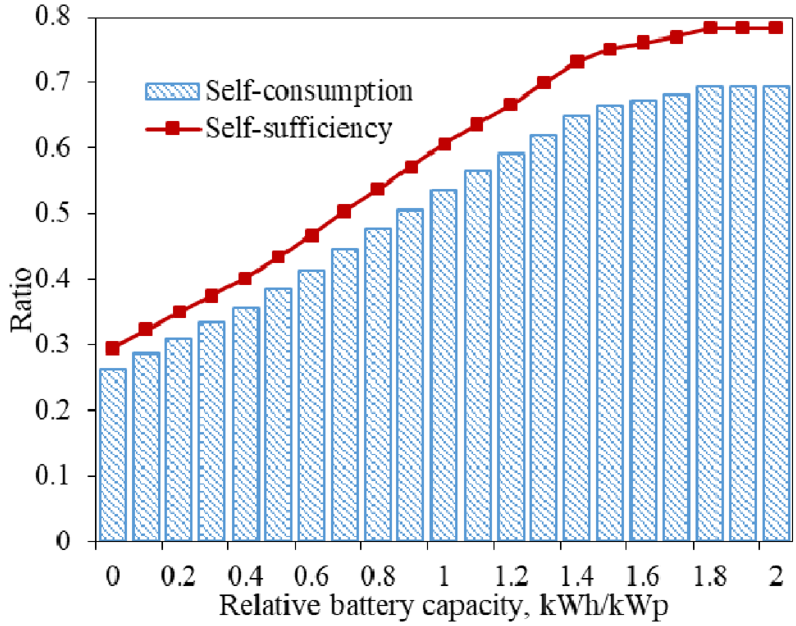


Fig.5-29. Self-consumption ratio and self-sufficiency degree of residential PV system (5.0 kWh) with different relative battery capacities

The differences of self-consumption rates in December become slightly with increasing battery capacity. As shown in Table 5-3, because the household features with a high initial self-consumption rate or reaching total PV electricity self-consumption in winter month, a battery with relatively small capacity is able to absorb excess PV generation. Initially the self-consumption rate increases more by adding a relative small size of the battery system in several months, since adequate excess PV generation could be shifted to fully exploit the storage capacity. When the PV system experiences its low generation periods, it may lead to an inadequate utilization of the battery with larger sizes, self-consumption rate enhancement will become saturated with increasing battery size under fixed PV capacity.

With the increasing aggregated capacity of distributed grid-connected PV system, it indicates a promising potential to increase local self-consumption and shift the grid load from bottom up approach optimization. Considering the characteristics of the grid demand curve, an optimal demand side management strategy is implemented to optimize the daily charging and discharging cycle of the battery system, mainly discharge the battery from 16:00 to 22:00 corresponding to the public peak period. The objectives aim at maximizing self-sufficiency for the household, meanwhile lowering the peak imported power from the public grid, achieving the potential to relieve peak pressure on the public grid. Due to the limitation of daily load profile, simulation results indicated that discharging ability of battery with 3.0 kWh capacity already fully covers the residential load during evening peak period, battery with larger size may increase self-consumption ratio but has to discharge energy at low electricity pricing stage that lower than current feed-in tariff, reducing the net profits. Meanwhile, increasing investment in storage will cause heavy burden to the customer. During the power dispatch process of the grid-connected household PV battery system, surplus power from PV system fed into the battery is indicated as negative value. Positive values present power bought from the grid, directly consumed electricity from the PV system and the output from the battery. When the battery is fully charged, excess generation will be delivered to the grid indicated as negative value. Fig.5-30 illustrates the dispatch power flows for the grid-supporting PV-battery system in August, high levels of participation in the proposed program means great potential to offset electricity load during peak hours.

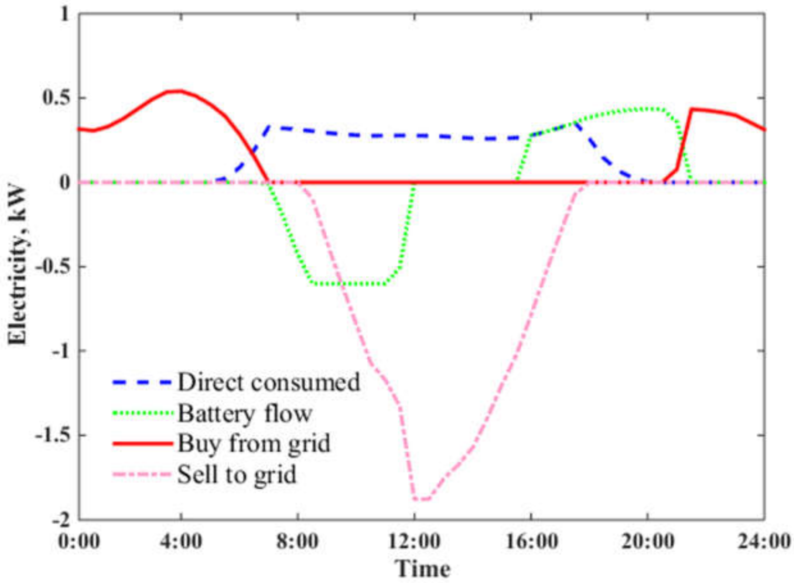


Fig.5-30. Power dispatch for the grid-connected household PV-battery system in August, PV capacity 5.0 kW$_p$ and battery size 3.0 kWh.

Table 5-3 The self-consumption ratios of the residential PV system with different battery sizes in each month

Size, kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.0	0.59	0.36	0.20	0.20	0.20	0.31	0.30	0.23	0.22	0.23	0.27	0.41
0.5	0.67	0.39	0.22	0.22	0.21	0.33	0.32	0.24	0.24	0.27	0.31	0.46
1.0	0.74	0.42	0.23	0.23	0.23	0.36	0.34	0.25	0.26	0.29	0.34	0.50
1.5	0.80	0.46	0.25	0.25	0.24	0.38	0.36	0.27	0.27	0.32	0.37	0.56
2.0	0.87	0.49	0.26	0.27	0.26	0.40	0.38	0.28	0.28	0.37	0.41	0.60
2.5	0.88	0.52	0.29	0.29	0.28	0.45	0.40	0.29	0.31	0.40	0.47	0.64
3.0	0.88	0.55	0.32	0.32	0.32	0.49	0.42	0.30	0.35	0.44	0.51	0.69
3.5	0.88	0.62	0.34	0.34	0.35	0.55	0.45	0.32	0.37	0.47	0.55	0.77
4.0	0.88	0.65	0.37	0.36	0.37	0.58	0.51	0.36	0.40	0.50	0.59	0.81
4.5	0.88	0.68	0.39	0.41	0.39	0.60	0.53	0.38	0.42	0.57	0.62	0.86
5.0	0.88	0.74	0.41	0.43	0.41	0.65	0.55	0.40	0.47	0.60	0.69	0.86
5.5	0.88	0.78	0.43	0.45	0.46	0.69	0.61	0.41	0.49	0.62	0.71	0.86
6.0	0.88	0.80	0.49	0.47	0.48	0.72	0.62	0.43	0.51	0.68	0.76	0.86
6.5	0.88	0.84	0.51	0.49	0.50	0.78	0.67	0.48	0.53	0.72	0.79	0.86
7.0	0.88	0.84	0.53	0.55	0.51	0.80	0.70	0.49	0.59	0.76	0.84	0.86
7.5	0.88	0.84	0.55	0.57	0.56	0.82	0.70	0.51	0.59	0.79	0.86	0.86
8.0	0.88	0.84	0.56	0.58	0.56	0.82	0.73	0.52	0.59	0.80	0.86	0.86
8.5	0.88	0.84	0.58	0.59	0.56	0.82	0.76	0.54	0.59	0.80	0.86	0.86
9.0	0.88	0.84	0.63	0.64	0.56	0.82	0.76	0.54	0.59	0.80	0.86	0.86
9.5	0.88	0.84	0.63	0.64	0.56	0.82	0.76	0.54	0.59	0.80	0.86	0.86
10.0	0.88	0.84	0.63	0.64	0.56	0.82	0.76	0.54	0.59	0.80	0.86	0.86

In order to analyze the technical and economic performance of residential PV system. Table 5-4 gives an overview of the relevant costs and assumed parameters for residential PV battery system.

Ignore the operation and maintenance cost, from a user perspective the payback period of residential PV battery system can be calculated by setting the NPV of the total investment to zero, considering the cash inflows (R_j) for the generic year j= [1,2,3,…n], and n is the number of year in the payback period. I stands for capacity investment for each variable, it is assumed that there is a second investment in battery after N_{bat} years.

$$\begin{aligned} NPV &= \sum_{j=1}^{n} R_j \cdot (1+i)^{-j} - C_0 \\ &= \sum_{j=1}^{n} R_j \cdot (1+i)^{-j} - (I_{pv} + I_{bat} \cdot [1 + \frac{1}{(1+i)^{N_{bat}}}]) \end{aligned} \quad \text{Eq.5-14}$$

Choosing the discount rate i equal to 4.0%, electricity price increases with 2.0% per annum. We calculated the number of years for alone PV systems NPV=0 in Eq.5-14. The cash inflow refers to the profits from electricity bill saving and feed in revenue. Fig.5-31 presents the net present value of the 5.0 kW_p household PV system over 20 years in Kyushu. High feed-in tariffs policy for PV power generation is not sustainable development for the future power supply system, there is a decreasing trend of the feed in tariff (FIT) under the large integrated PV scenario in current public grid. Sensitivity analysis was performed to identify the financial impact by changing PV feed in pricing from 0.021$/kWh to 0.015$/kWh, lower FIT will extend the payback period.

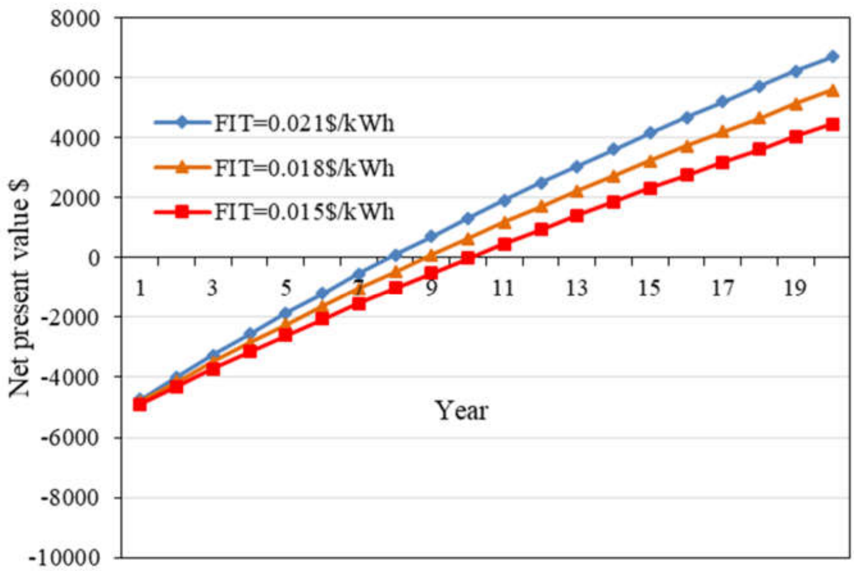


Fig.5-31. Net present values of PV system under different feed in tariffs, PV 5.0 kW_p capacity without battery

Table 5-4 Input data for the residential PV-battery systems used in the model [6,7]

Variables	Value
PV cost	1100 $/kW
PV lifetime	20 year
Battery (lithium ion) cost	600 $/kWh
Battery lifetime	10 year
Discount rate	4% per annum
Increase in electricity price	2% per annum

The PV self-consumption ratio will increase by adding the battery, it can help reduce the electricity consumption cost, minimize the loss revenue from sold electricity when the FIT decreases. Add battery will increase the initial investment, and enlarge the payback period as illustrated in Fig.5-32. Future drop in the capital cost and PV feed-in tariff may enhance the economic performance of the PV-battery system.

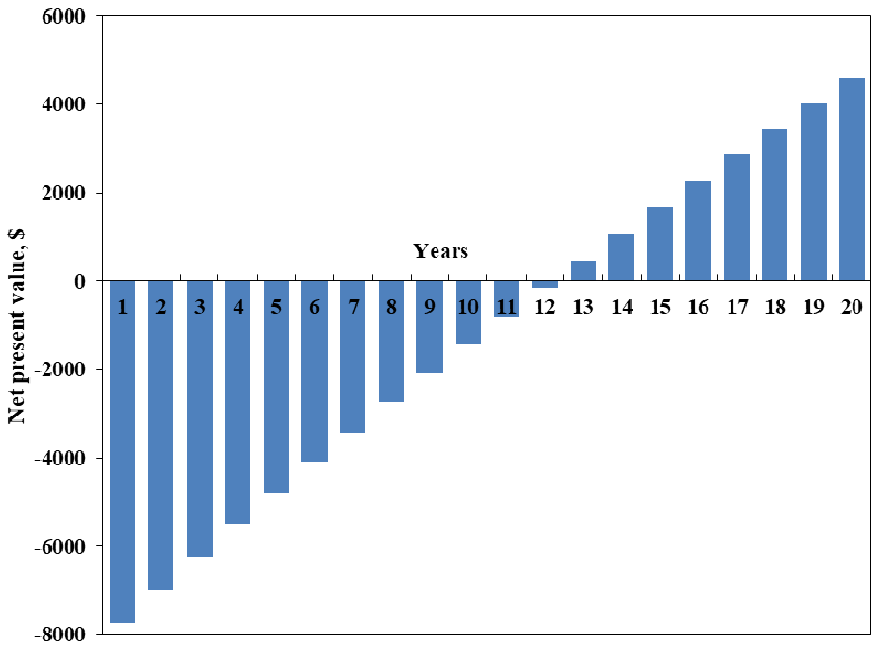


Fig.5-32. Net present value of typical residential PV-battery system, PV 5.0 kWp, battery capacity with 3.0 kWh

5.4.5 Conclusion

The proposed residential PV battery model is applied and evaluated in typical household of Kyushu, main conclusions of this research are summarized as follows:

(1). PV self-consumption ratio increases in non-linear with increasing battery sizes and becomes saturated at relative greater storage capacity.

(2). Self-consumption rates show great variations between months, self-consumption rate presents high value during the winter season due to the relatively low PV generating ability, it will firstly come into saturated condition with increasing battery size.

(3). Incentive subsidy to battery unit is essential to shorten the payback period of the proposed grid-supporting residential PV battery system.

5.5 Application of residential PV-CHP hybrid system

Japan's ENE-FARM program is arguably the most successful fuel cell commercialization program in the world. The fuel cell (ENE FARM) devices, packaged in enclosures about the size of a refrigerator, convert natural gas into electricity and heat that can be used for hot water and space warming. Their maximum electric output is 700 watts. Panasonic, one of the main producers of the devices, claims 95% total energy efficiency, the units operate in partnership with the grid, cycling on and off in response to the home's demand for electricity and hot water. The units yield savings on energy bills of ¥60,000 – ¥70,000 ($531– $619) per year, as much as reduction 50% of household CO2 emissions.

Economics are critical to consumer acceptance of the Ene Farm product. The price of the units at the time of introduction was 2.8 million ¥ (24,800 $) but a government subsidy of 1.4 million ¥ (12,400 $) brought the net cost to the customer down to 1.4 million ¥ (12,400 $). Uptake experienced steady growth from 2,300 units in 2009, the year of commercial introduction, to 30,000-40,000 units in 2016 as shown in Fig.5-33. The central government has set targets that call for an installed base of 1.4 million units by 2020 and 5.3 million units by 2030. Japan currently has about 50 million households. The price and subsidy have come down in recent years, it is estimated that the payback period is approximately 18 years for a net cost 10,600 $ after relevant subsidy.

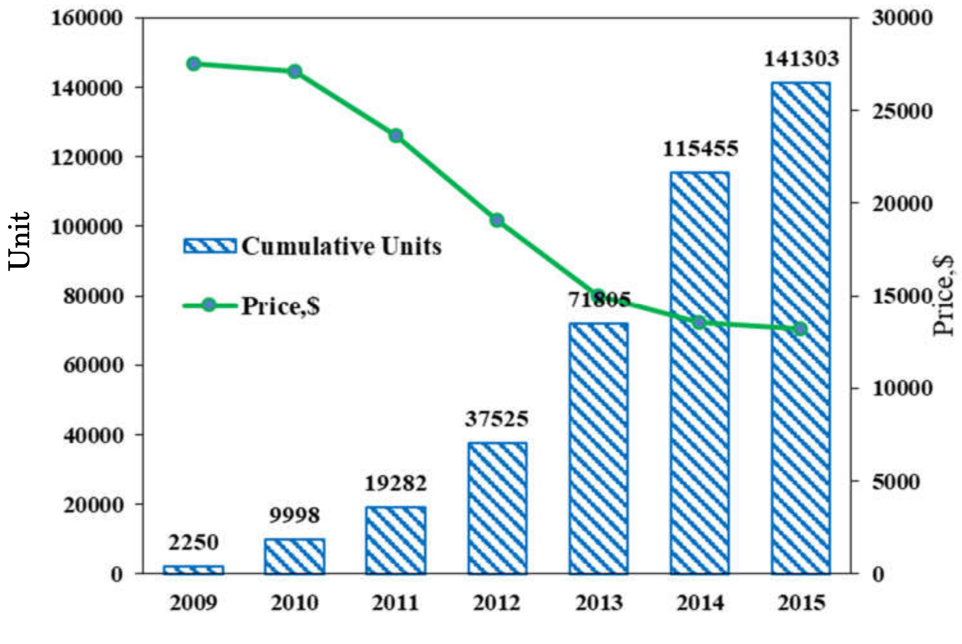


Fig.5-33. Parameters of market uptake for fuel cell units, reference: On the Ground in Japan: Residential Fuel Cells

This section investigates the techno-economic performances of residential house with hybrid PV/fuel cell power system in Kitakyushu, Japan. Fig.5-34 presents the detail structure of the hybrid energy system in Jono area. Firstly, classified the electricity consumption and on-site generations from PV/fuel cell system. Then analyzed the load matching and grid interaction performances, based on realistic measured data. The net profit and payback period for the customer were calculated according to the electricity market and energy cost. Finally, assessed the ZEH economic feasibility and environmental benefits.

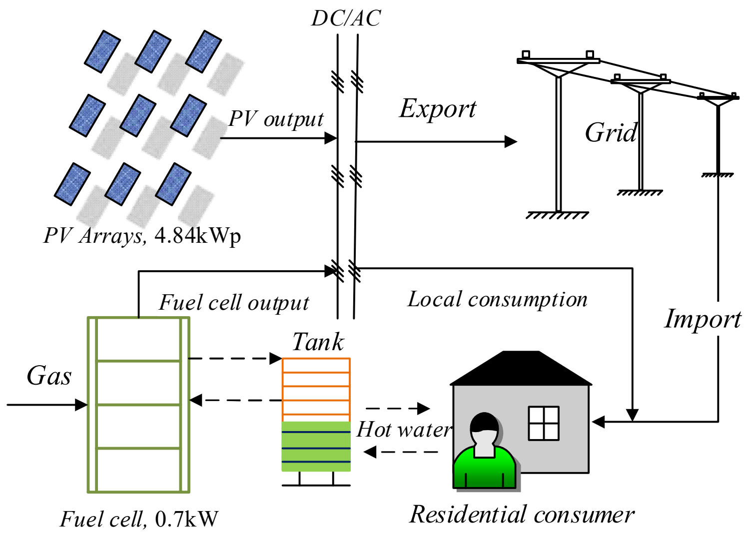


Fig.5-34. Structure of the household hybrid PV/fuel cell energy system

5.5.1 Objective

This part will describe the characteristics of the residential house, power components in the hybrid energy system and the energy supply. The building covers 169.91 m^2 and composed of two stories, net area of first floor measures 66.41 m^2 featured with floor radiant heating, second floor measures 56.26 m^2, average U-value of the wall is 0.58 $W/(m^2 \cdot K)$. There are four people in this family with couples and two children. As shown in Fig.5-34, the capacity of installed PV module is 4.84 kW_p located in south and west rooftops considering the house southwest orientation, fuel cell is 0.70 kW nominal output equipped with 140 L thermal tank for hot water storage, cogeneration runs in combined heating and power mode tracking thermal load. Grid connection capacity of the smart house is a 50A contrast with Kyuden Electrical Company. When the produced PV electrical power is over the residential electrical demand, excess generation will be fed into the grid. If the total productions from PV and fuel cell are still unable to cover the simultaneous demand, electricity will be imported from the grid to cover the shortage. Electricity tariff structure features with foundational charge and different amount stage chargers, a typical agreement between public grid and smart house (8, 9). Therefore, the installation of on-site generator indicates a good chance for the customer to reduce the electricity bill. Table 5-5 reports the technical components and detail parameter values of the zero energy house (ZEH) energy system.

Table 5-5 Characteristics of the hybrid energy system and household

	Variables	Technical parameters
Power generators	PV	Nominal capacity 4.84 kWp, 15.5% efficiency.
	Fuel cell	Panassonic, 0.70 kW /1.01 kW (power/thermal) nominal capacity, electricity efficiency 39.0% , thermal efficiency 46.0% (LHV), with 140L,40 ^{o}C hot water. Thermal load is the sum of life hot water supply and radiant floor heating load.
Electricity market	FIT	0.22 $/kWh feed-in tariff (FIT) for PV generation.
	Price	Monthly foundational charge, 13.3$/kWh (50 A). Electricity price depends on the range of total consumption: 0.16 $/kWh within 120 kWh/month, 0.21 $/kWh within 120~300 kWh/month, 0.22 $/kWh over 300kWh.
Power consumptio n	Home Appliances	AC1 in living room cooling capacity 5.6kW (2.07kW), heating mode 6.7kW (1.9kW); AC2 in bedroom cooling capacity 2.8kW (3.94 kW), heating mode 3.6kW (0.86kW); AC3 for free space cooling capacity 4.0kW (0.89kW), heating mode 5.0kW (0.98kW); Washing machine 0.5kW; Dishwasher 0.2 kW; TV 0.15kW; Refrigerator 0.09kW.

Note: Air conditioner (AC) nominal capacity (electricity consumption).

According to the patterns and constraints of the daily electrical and thermal load profiles, the HEMS can automatically control the daily operations process of the cogeneration unit. Thermal storage tank enables the fuel cell to operate at near full load and absorb the waste gas heat as much as possible. As shown in Fig.5-35, the power output of fuel cell is limited to the electricity demand and its nominal capacity (0.70 kW). The cogeneration system runs with thermal tracking strategy and on-off operation cycle of the fuel cell is controlled by the energy consumption patterns and amount of hot water in thermal storage tank.

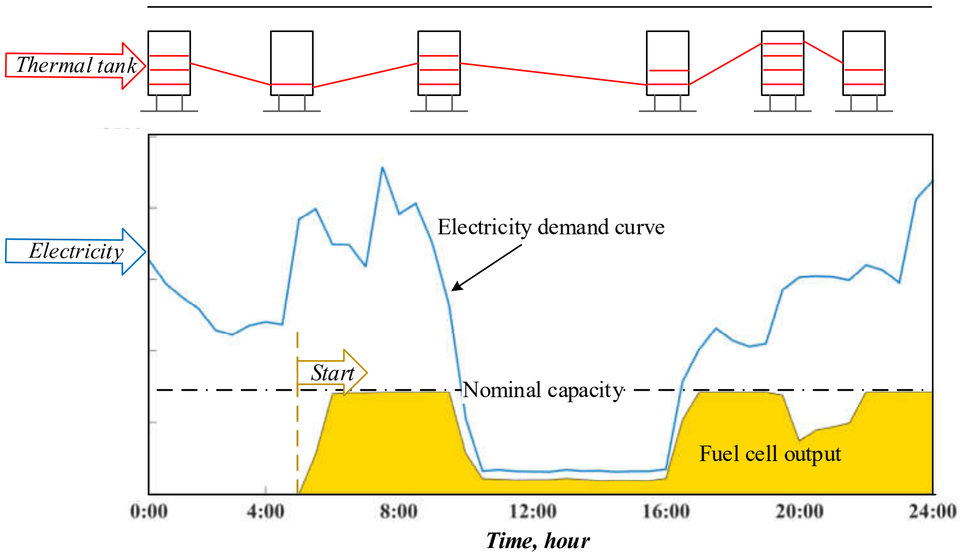


Fig.5-35. Operational CHP mode of fuel cell in a typical day

Energy saving of CHP system should consider the performance both the centralized production and distributed energy system. Set 39% electrical efficiency of fuel cell 52% thermal efficiency, 40% efficiency for centralized plant. Fig.5-36 shows the primary energy performances of different prime movers according to different demand-side heat to power ratios in combined heating and power mode, the vertical axis is the primary energy consumption ratio between cogeneration system and separate production system. It should be noted that the CHP system shows energy saving potential when the ratio value is under the blue dash line. The demand-side heat to power ratio has a greater influence on the power unit with higher electrical efficiency. In the right of red dot line, the curves 'O-Q' presents the electrical demand is fully covered, the boiler makes contribution to thermal demand; 'O-S' presents that the prime mover can cover the heat load, the surplus electricity can't be utilized further, which is usually common in the isolated CHP mode. In the wright of the red dot line, the curves 'O-P' presents the prime mover can covers the demand heat load without boiler contribution, the public electricity feeding in to cover the excess power demand; 'O-R' indicates that the electricity load can be fully covered by CHP system, however the surplus heat energy is lost as waste heat. It is obvious to observe that the CHP system shows the best primary energy saving performance in point 'O', when the total user's demand (heat and power) is identical with productions from the prime power units. The power units with higher electricity efficiency and overall efficiency can reach the better possible energy saving point, as shown in Fig.5-36. The possible energy saving values of fuel cell can reach 35% at point ‘O’.

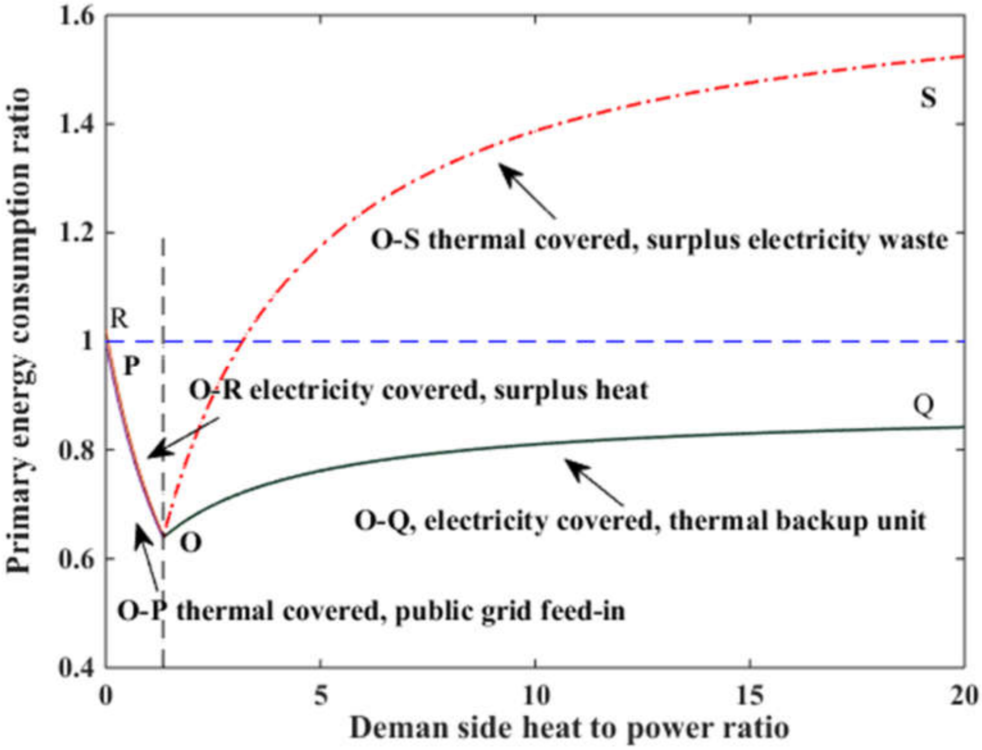


Fig.5-36. Primary energy saving performance of fuel cell cogeneration system

5.5.2 Electricity generation and consumption load

HEMS enables automatic control of the household appliances and on-site power generators of the Net ZEH, meanwhile monitors the power generation of on-site generators and the power exchanges with the public grid. We collected the monitored data of the ZEH energy systems at 60 min interval over half year period that lasts from July 1th to December 31th in 2017, including separate measurements of power consumptions in the kitchen, living room, dining room and toilet, and the main home appliances including: washing machine, dishwasher and air conditioners as shown in Table 5-6.

The duration curves of demand load and power contributions from fuel cell and PV from July, 1th to December 31th are shown in Fig.5-37. Fuel cell and the consumed PV generations cover 27.0%, 19.0% of total household demand respectively, 54.0% of power imported from the public grid for real time balance. As shown in Fig.5-38, for the local demand-supply balance, larger amount of local generation has to be exported to the grid during the summer and autumn compared with winter condition. Due to the weather condition, the daily electricity load is relatively high and fuel cell shows an increasing cover ratio during winter day, whereas the PV is experiencing its low generating ability period, there are less reverse power flows fed into the grid. Detail results of the power balance of ZEH energy system, including power exchanges and ratios are summarized in Table 5-6. The net grid load is 198.4 kWh, a sum of the imports and exports that close to 'net zero' compared with total power consumption over six months.

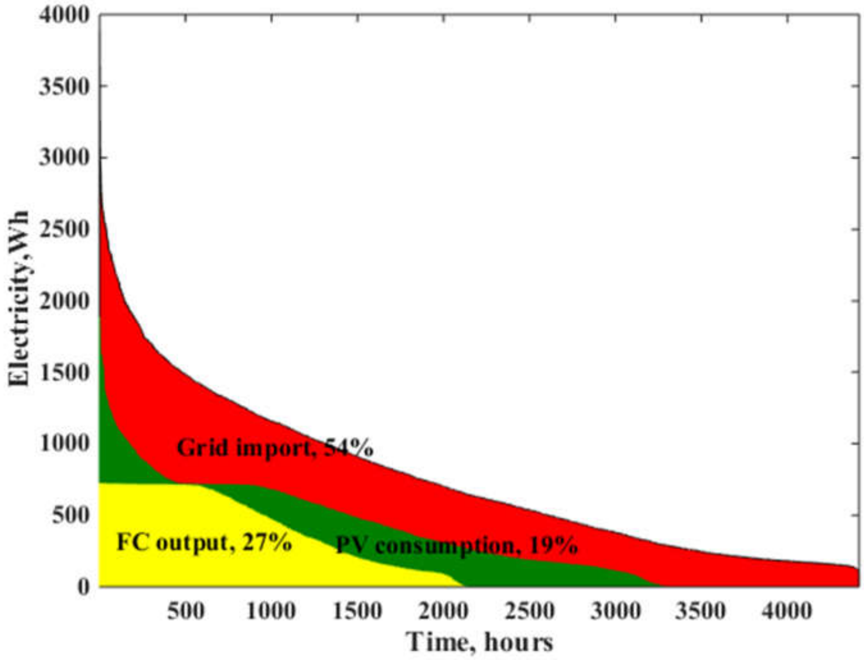


Fig.5-37. Sorted duration curves of fuel cell output, directly PV consumption and demand load

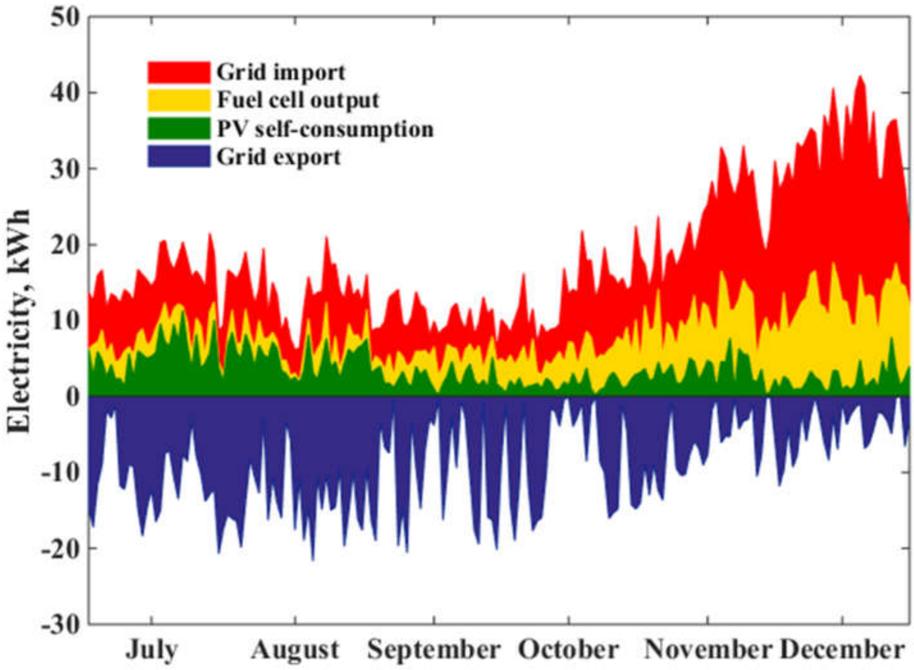


Fig.5-38. The daily power balancing situation for the ZEH with grid-tied hybrid power system

Table 5-6 Results of the power balance of ZEH from July to December

	Fuel cell	PV consumption	Export	Import	Net load	Demand load
Power (kWh)	900.4	628.1	-1646.6	1845.0	198.4	3372.5
Ratio	0.27	0.19	-0.49	0.55	0.059	1.0

Fig.5-39 demonstrates the variability of measured electricity consumption composed of air conditioner and other electric appliance parts. The electricity demands show significant seasonal variations from July to December, the reason is that air conditioning consumption for space heating contributes significantly to the daily load. In addition, the air conditioning load is a function of outdoor weather condition and it was distinguished for cooling and heating modes that further increased the daily demand variability. It is conceived that electricity consumed for cooling is generally smaller than electricity for heating mode due to the cold weather climate in winter. Table 5-7 classifies the detail electricity consumption and ratios for different rooms and electric appliances in detail, air conditioners shared the largest electricity consumption ratio of the household 47.0%, power consumptions for the kitchen features with the next largest value, 15.0%.

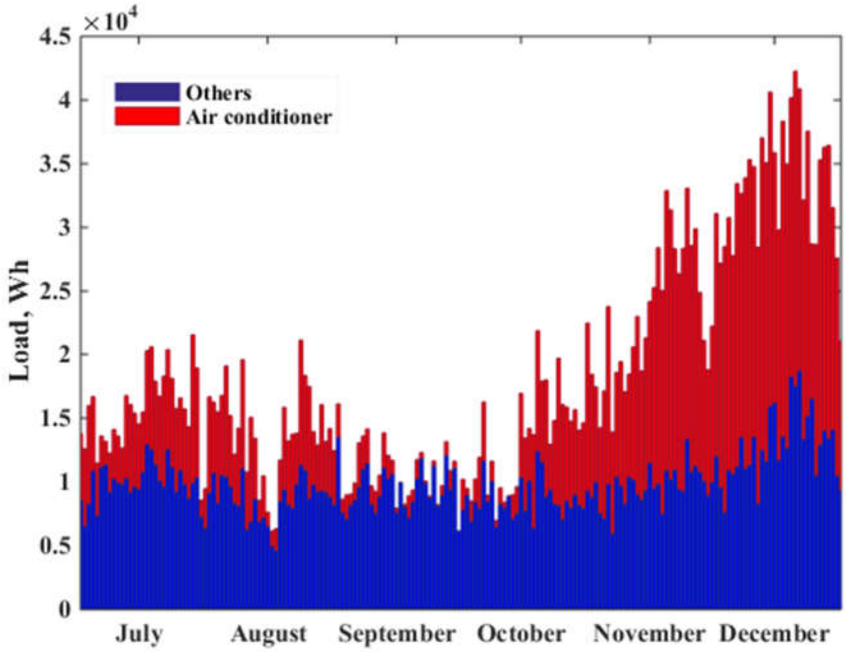
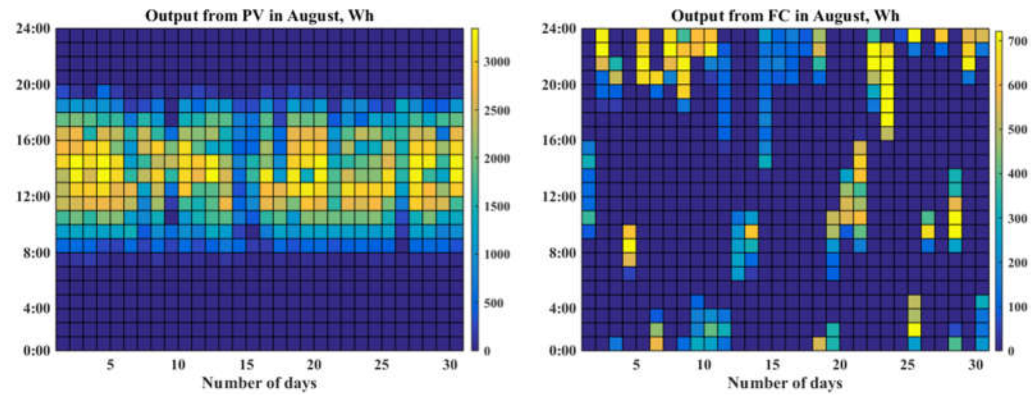


Fig.5-39. Daily electricity consumptions of air conditioner and other home appliances

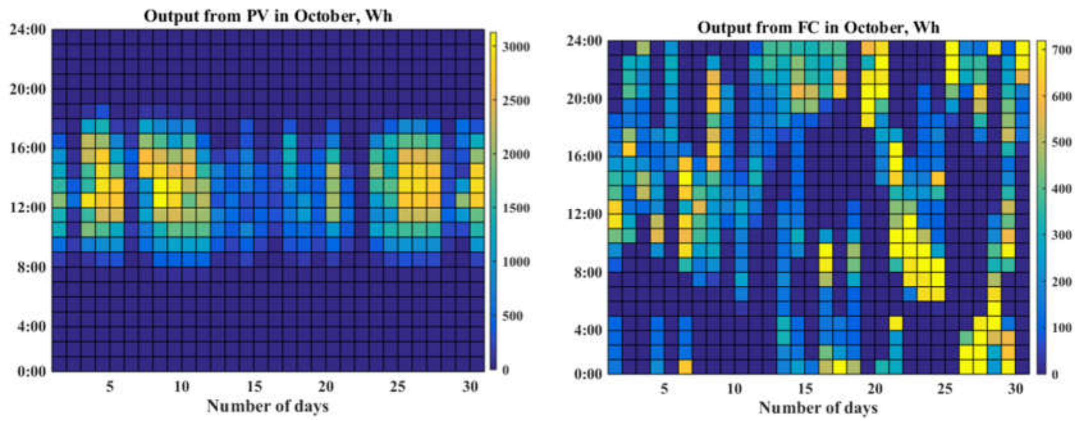
Table 5-7 Electricity consumption for different spaces and main home appliances

Type	Kitche	Dining	Living	Bathroom	Toile	Dishwasher	Washing	Air	Other
Load	525.57	51.63	241.83	115.73	120.0	120.47	178.60	1673.56	535.6
Ratio	0.15	0.014	0.068	0.032	0.034	0.034	0.050	0.47	0.15

a)



b)



c)

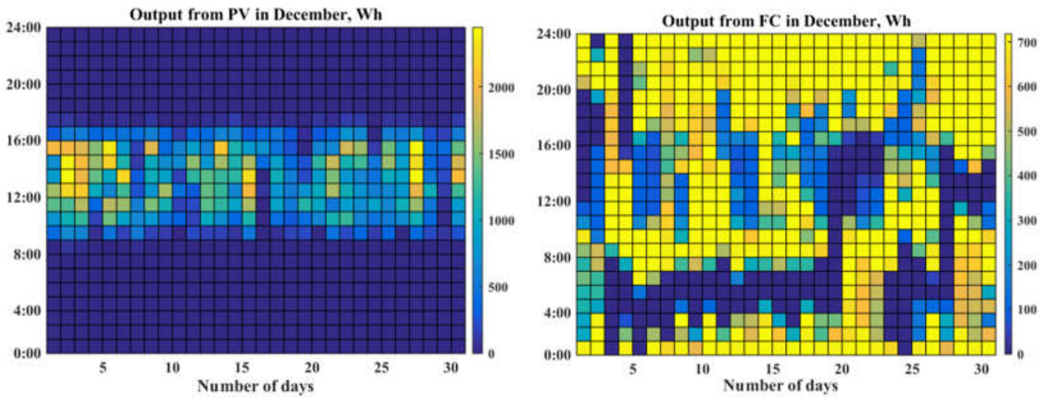
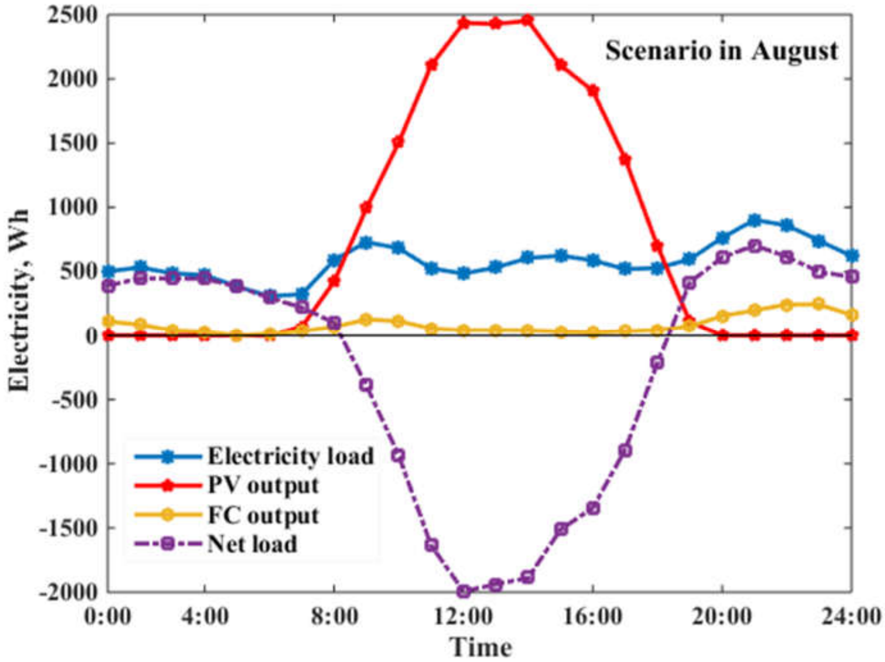


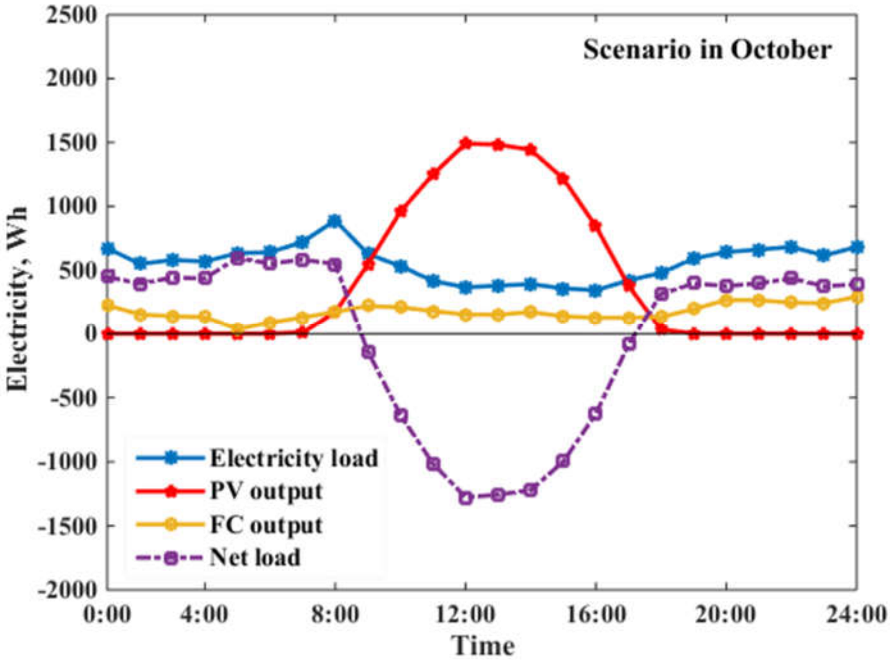
Fig.5-40. Color scale distributions of daily PV output and FC generation of the Net ZEH in August, October and January

Considering the seasonal variations, Fig.5-40 (a)-(c) demonstrate the detail daily variabilities of PV and Fuel cell outputs in color scale for August, October and December, which can present the summer, mid-season and winter, respectively. The daily PV generation pattern changes significantly between these months, including the generating capacity and effective utilization hours. PV generations has the longest time to generate electricity in August and the shortest in January, the generation capacity reaches its maximum utilization factor in August and is particularly limited in December. The operation periods and productions of fuel cell show significant variations between months. Its operation condition has a close relationship with the daily thermal load, it features with larger output and longer generating period in December, and fuel cell could nearly operate at its rated capacity throughout the whole day. Fig.5-41 (a)-(c) presents the average hourly matching scenarios of the hybrid energy system in August, October and December respectively, including the demand load (blue line), the power flows from PV (red line) and fuel cell (yellow line), and the net grid load (purple line) that the feed-in power is indicated as negative value.

a)


Scenario in August
Electricity, Wh
Time
Electricity load
PV output
FC output
Net load
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0:00
4:00
8:00
12:00
16:00
20:00
24:00

b)


Scenario in October
Electricity, Wh
Time
Electricity load
PV output
FC output
Net load
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0:00
4:00
8:00
12:00
16:00
20:00
24:00

c)

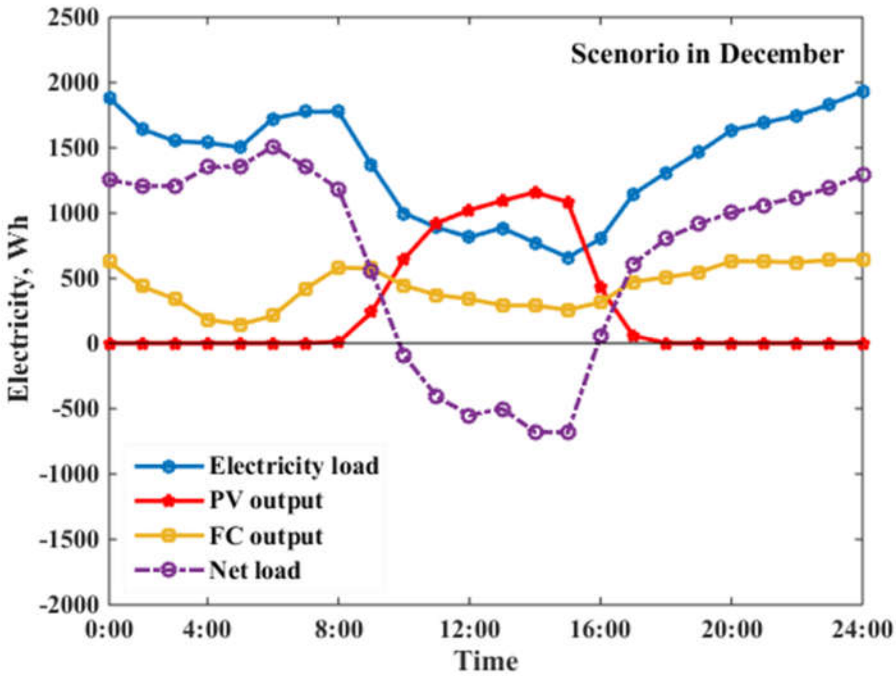


Fig.5-41. Daily power matching scenarios of the grid-tied Net ZEH: average hourly electricity load, PV output, FC generation and net load profiles in August (a), October (b) and December (c)

The PV self-sufficiency ratios are higher in August, 36.5% on average, this is driven by the fact that electricity consumptions increase for space cooling, meanwhile PV system is experiencing its maximum generating ability to cover loads during daytime, and fuel cell contributes less due to the limited thermal demand. This also increases the PV direct self-consumption ratios, however, there is still a large amount of excess PV production exported to the grid due to the limited PV self-consumption ability. Load cover ratios by fuel cell increase via tracking the increasing thermal load in October, significant ratio of the PV generation has to be fed into the grid due to the limited net electricity load during off-peak daytime period, and the PV direct self-consumption ratios drop. The household features with larger electricity demand in December, high thermal loads enable the fuel cell to operate at near full load during early morning and night periods to offset the electricity imported from the grid. PV system shows low generating ability due to the low irradiance period, higher demand load compared with August and October enables customer to consume more local PV generation during daytime, and direct PV self-consumption ratios increase, less reverse flows fed into the grid.

5.5.3 Analysis and results

In order to understand the economic and environmental performances of the ZEH energy system, this part mainly makes a comparison of the household with and without the hybrid energy supply system according to the electricity balance results summarized in Table 5-8.

Table 5-8 Contribution of each power resource and power balancing scenario of Net ZEH for different months.

Month	Demand	FC output	PV output	PV self-	Grid import	Grid export
July	481.3	81.1	513.3	167.6	232.5	-345.7
August	430.6	62.1	576.7	157.3	211.2	-419.4
September	319.3	85.7	379.3	78.5	155.1	-300.9
October	416.5	129.8	304.4	52.4	234.3	-252.0
November	687.1	212.5	294.0	100.5	374.1	-193.6
December	1034.2	327.0	206.8	71.7	635.4	-135.1

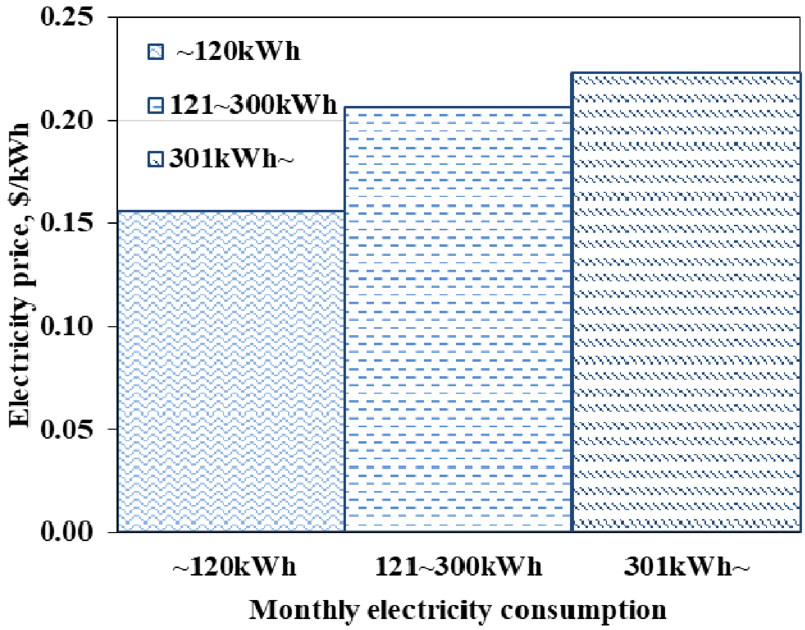


Fig.5-42. Typical electricity tariff structure for smart residential household with on-site generator

Fig.5-42 shows the current electricity tariff scheme for the ZEH. For this household, monthly fixed foundational charge is 13.3$/kWh (50A). Unit electricity price depends on the range of total consumption: 0.16 $/kWh within 120 kWh/month, 0.21 $/kWh within 120~300 kWh/month, 0.22 $/kWh over 300kWh. It could be found that monthly electricity consumption of the household generally excesses 300 kWh, indicating a promising electricity bill saving potential by introducing local generations to reduce imported electricity from the grid. Choosing feed-in tariff of PV 0.255 $/kWh, household natural gas price 1.86 $/Nm3, lower heating value 45.0 MJ/Nm3 (30). As shown in Fig.5-43, the monthly profit components, including gas bill saving, sold electricity profit and electricity bill saving that were calculated corresponding to the power balancing results depicted in

Table 5-8. Net profit in August is higher compared with other months, the exported local generation brings a great income to the customer. Increasing electricity demand and relatively low PV generating capacity causes a net profits drop during mid-season. The gas driven fuel cell can share a larger load ratio to reduce the electricity bill in December. Although a large amount of waste gas heat is recycled for hot water and floor heating supply, the monthly net profit drops due to the rise in gas consumption cost for greater amount of electricity generations and limited PV productions. Table 5-9 illustrates the cost and technical input parameters for economic and environmental assessments.

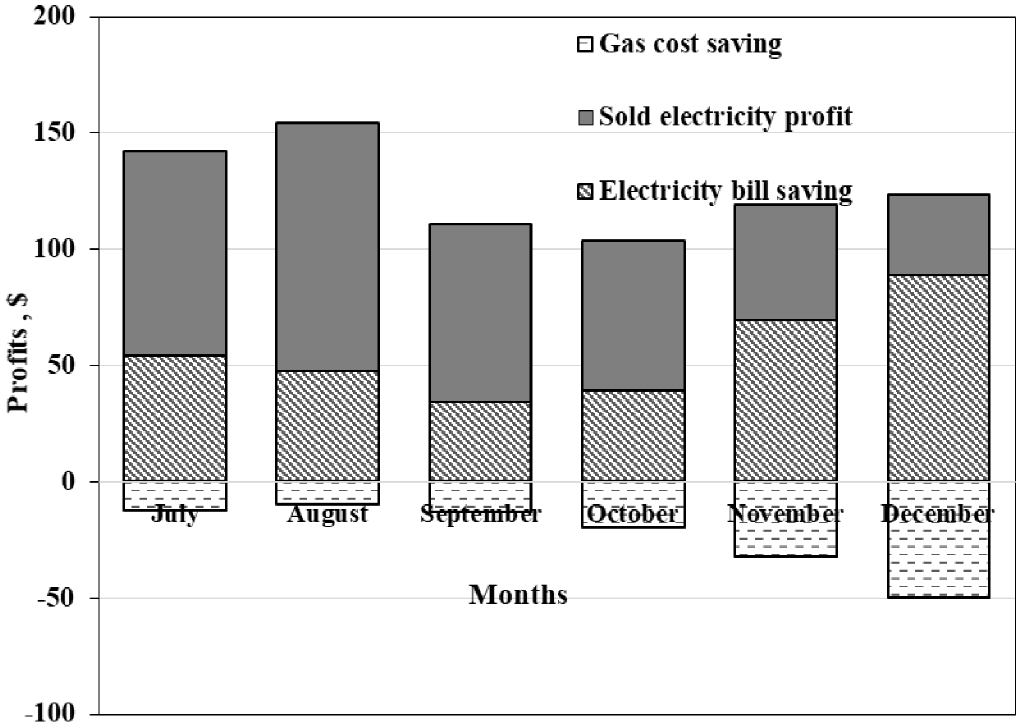


Fig.5-43. Profit components of the ZEH with hybrid energy system (PV system 4.84 kWp, Fuel cell 0.70 kW) from July 2017 to December 2017

Table 5-9 Cost and technical input parameters of the hybrid energy system [9, 10]

Variables	Kyuden grid	PV system	Fuel cell
Capacity	50 A	4.84 kW_p	0.7 kW
Lifetime	nan	20 year	10 year
Investment	nan	1100 $/kW_p$	13000 $
CO_2	0.483 kg/kWh	0.0 kg/kWh	0.470 kg/kWh

In order to investigate the economic performance of the hybrid energy system (PV capacity, 4.84 kW_p, fuel cell output, 0.70 kW), choosing the annual discount rate *i* equals to 4.0% and average net profit 102.7$ per month as shown in Fig.5-43, the twenty year net present value (NPV) performances of the hybrid energy system were carried out considering future capital drop in power technologies as shown in Fig.5-44, based on parameters values in Table 5-9.

$$\begin{aligned} NPV &= \sum_{j=1}^{n} R_j \cdot (1+i)^{-j} - C_0 \\ &= \sum_{j=1}^{n} R_j \cdot (1+i)^{-j} - (I_{pv} + I_{FC}(1 + \frac{1}{(1+i)^{N_{FC}}})) \end{aligned} \quad \text{Eq 5-15}$$

As given in Eq 5-15, the cash inflows (R_j) refers to the annual net profit for the generic year j=[1,2,…,n], C_0 presents the installation cost that mainly composed of PV I_{PV} and fuel cell system I_{FC}, it is assumed that there is a replacement investment in fuel cell after its lifetime N_{FC} years.

Choosing electric efficiency 39.0%, thermal efficiency 46.0% for fuel cell and 85.0% thermal efficiency for conventional hot water boiler, assume the CO_2 emission factor of nature gas is 2.29 kg/Nm^3 (12). The annual CO_2 emission productions of the household with and without hybrid energy system were estimated based on power balance results in Table 5-8 and technical parameter values in Table 5-9, respectively. The estimated annual CO_2 emission reduction is around 2678kg, as shown in Fig.5-45, the amount of thermal load refers to the recycled waste gas heat.

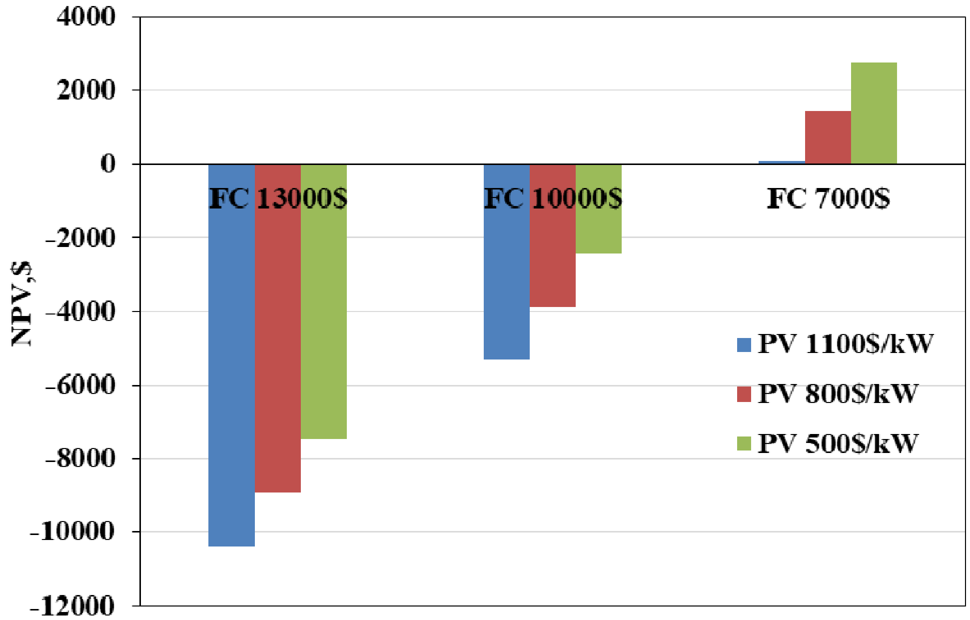


Fig.5-44. Net present value of the residential hybrid energy system, considering future capital cost drop in PV and fuel cell unit

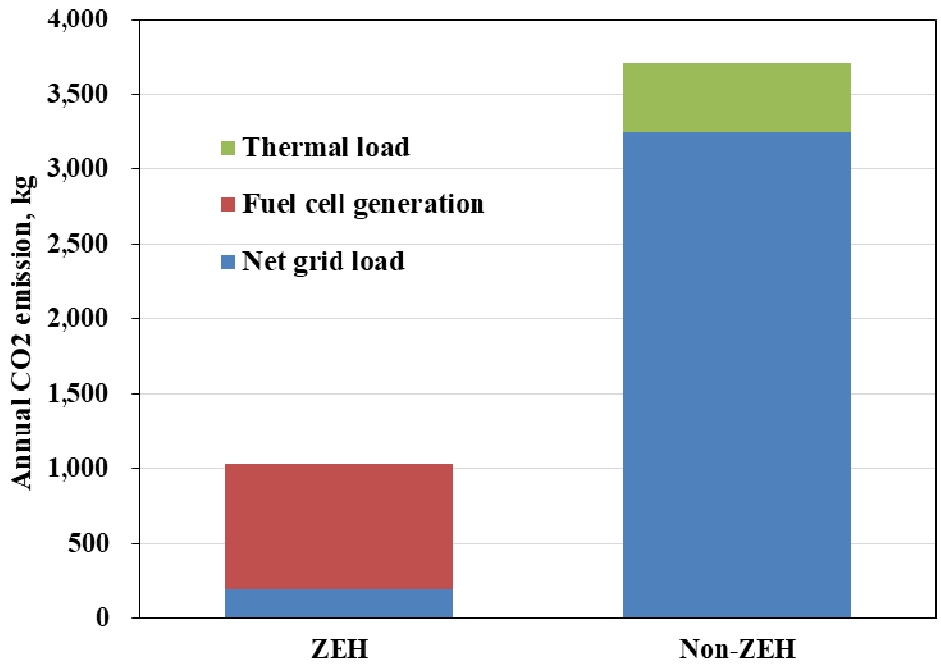


Fig.5-45. Comparison of annual CO_2 emissions of ZEH and residential house without hybrid energy system.

5.5.5 Conclusion

This work investigated the performances of a typical Net ZEH with grid-connected hybrid PV/fuel cell energy system in Kitakyushu, Japan, in terms of electricity generation/consumption scenario, load matching and grid interaction performances, economic and environmental assessments. The grid-tied hybrid energy system features with PV capacity 4.84 kWp, fuel cell cogeneration system with nominal output 0.70kW and 140L hot water storage tank.

Firstly, classified the household electricity consumption and generations, the energy consumption of the air conditioner for space heating has a significant impact on electricity demand in winter months. Fuel cell and PV share percentages of household demand 27.0%, 19.0% respectively over the period that lasts from July to December, based on realistic data. Excess PV generations result in significant reverse flows during summer or mid-season, operation period and output of fuel cell limit to the relatively low thermal load. Daily electricity consumption in winter is higher than summer and mid-season periods, fuel cell operates at near full nominal output with longer generating period via thermal load tracking strategy, and covers 32.0% of local electricity consumption in December.

Load cover ratios of the hybrid energy system have a close relationship with the correlation between household demand and on-site generation profiles. PV self-sufficiency ratios show great variabilities between months, it will drop due to its limited production and high demand in winter. Introduction of fuel cell provides a favorable result in increasing local self-sufficiency ratio instead of merely increasing PV size that may lead significant reverse flows that increase the reliability of the on-site generations and reduces negative impact on the grid.

Considering the current electricity tariff structure and energy cost, the average net profit is around 102.7$ per month. PV significantly contributes to the sold profits in summer and the fuel cell shows a preferable electricity bill saving in cold days. The simple payback time for the hybrid energy system is highly dependent the access to fuel cell subsidy scheme, the high initial investment is still the main obstacle to its wide development. Thanks to the PV productions and utilization of recycled waste gas heat, CO_2 emissions are attractively minimized from the household perspective. The decreasing fuel cell installation cost, rising energy cost and proper social supported incentive scheme can make the proposed hybrid energy system more acceptable for residential customers.

5.6 Grid impacts

5.6.1 Load demand curve

History public grid load are collected from Kyuden Power Company website at hourly interval over 2017, Fig.5-46 describes the daily average demand curves in public grid. During mid-season month it shows a relative flatten daily demand curve. Higher daily variations occur in summer and winter seasons due to the rising air conditioning loads, the average summer peak load driven by the massive cooling demand reaches around 14000 MWh as much as the 1.6 times of valley load. We cannot ignore that it may lead underestimated variations in daily demand curve by averaging time series over a day of month. Daily load in winter generally experience two periods in morning and night driven by the rising heating demand. Load leveling and peak load shifting has become important emissions for the grid utilities with concerns of power balancing security and quality maintenance, especially during the summer and winter seasons.

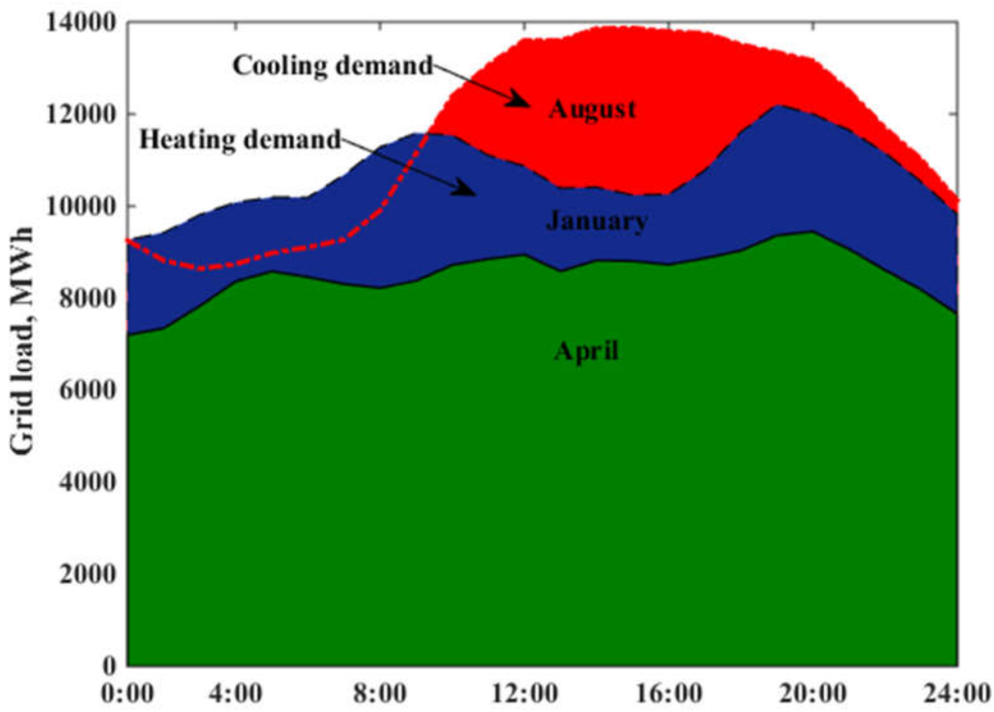


Fig.5-46. Average daily grid demand curves in different months of Kyushu region

5.5.2 Load leveling impact

Currently, residential sector accounts for around 33 % of total social power consumption in Japan. This part takes the bottom-up engineering approach to estimate the real world public grid impacts from aggregated residential high efficiency energy technologies. Assuming the load shape effects have a linear relationship with and the participation rate of high efficiency technologies, we will estimate the load levelling potential for 500 thousand participants for above mentioned technologies, respectively. Considering the need of load leveling and power balancing pressure mainly occur in air conditioning seasons, we will examine the daily load shifting performances in August and January. As shown in Fig.5-47, red dot line presents the original daily demand curves in August, cooling demand lead two peak periods at daytime and early night. The EVs and heat pump water heater mainly bottom up the valley load during deep night and early morning, PV system experience its large generating ability coincides with grid daytime peak period, fuel cell contributes less to the daily power consumption greatly limited to the lower heating demand in summer period. Released energy from EVs can effectively shave the night peak load in absence of PV production.

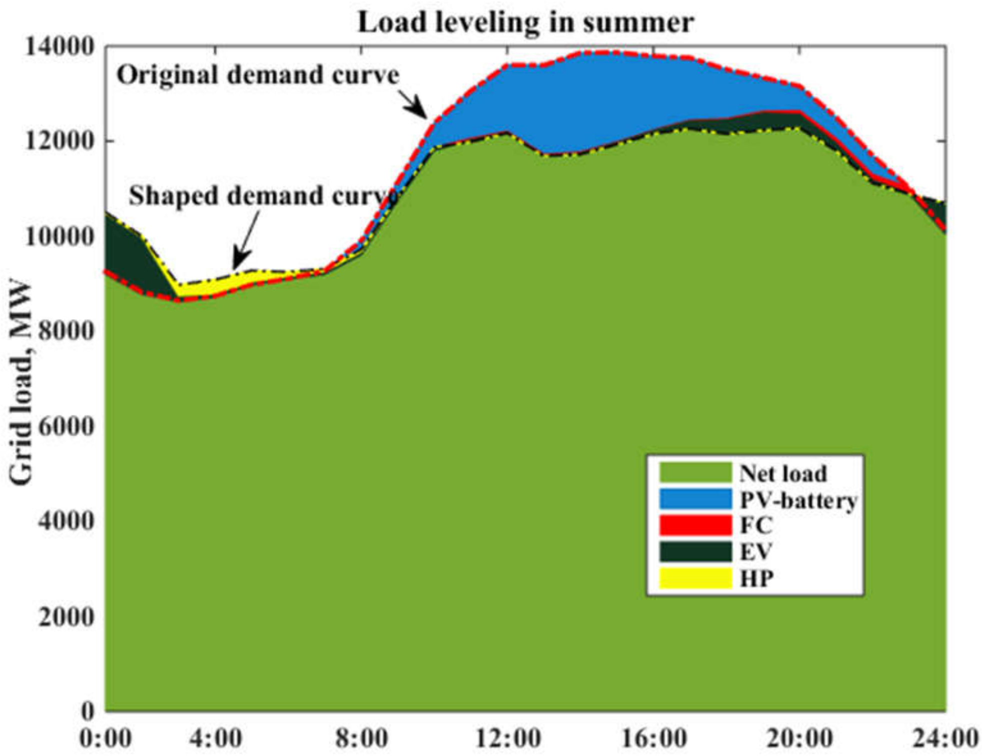


Fig.5-47. Load leveling effects of demand side management on public grid in summer

Fig.5-48 presents the load shifting scenario in January, daily load in red dot line increases in the early morning and after dinner time, which convinces the peak demand contribution from residential sector. Accompanying with rising the heating demand including hot water and space heating, fuel cell will contribute more to the residential daily load. Heat pump will consume more electricity to meet the daily increasing heat demand and lift more in grid valley period. PV shows lower generating ability compared with summer period and has low correlation with the grid load, it should be noted that high PV penetration may lead the ‘duck curve’ to increase the net load fluctuation. Scheduled PV-battery, EVs and fuel cell jointly contribute to the 8.0% of peak reduction at 20:00, enhancing the daily grid flexibility. The effect of demand side management forms a virtual power plant, which take place role of higher run cost of peak-meet plant. The coordinate demand side management can further decrease the overall generation cost as illustrated in Fig.4-49.

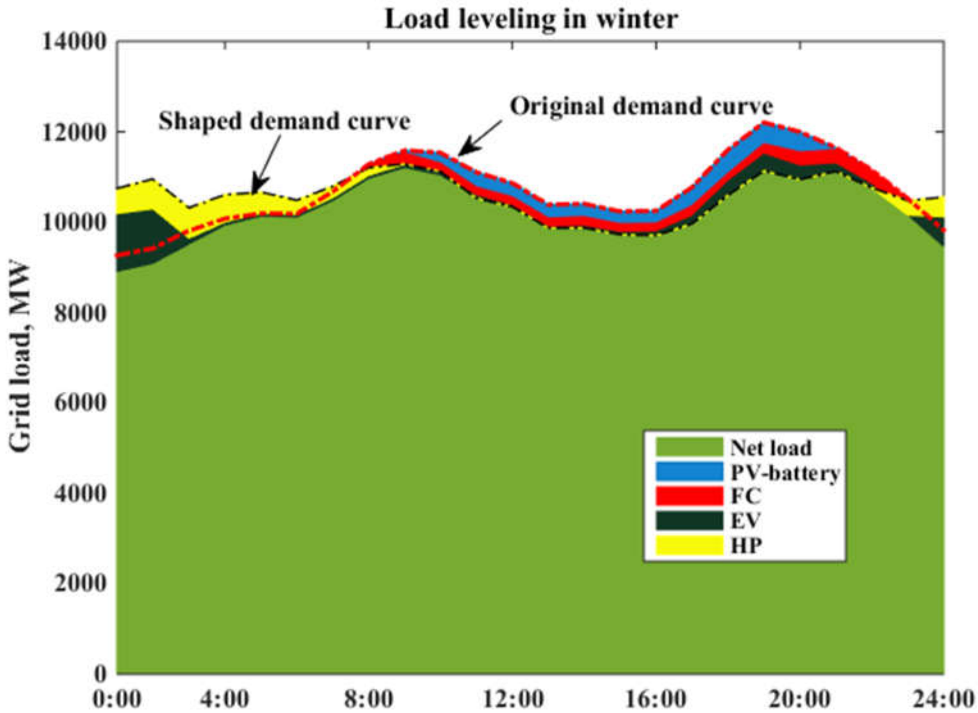


Fig.5-48. Load leveling effects of demand side management on public grid in winter

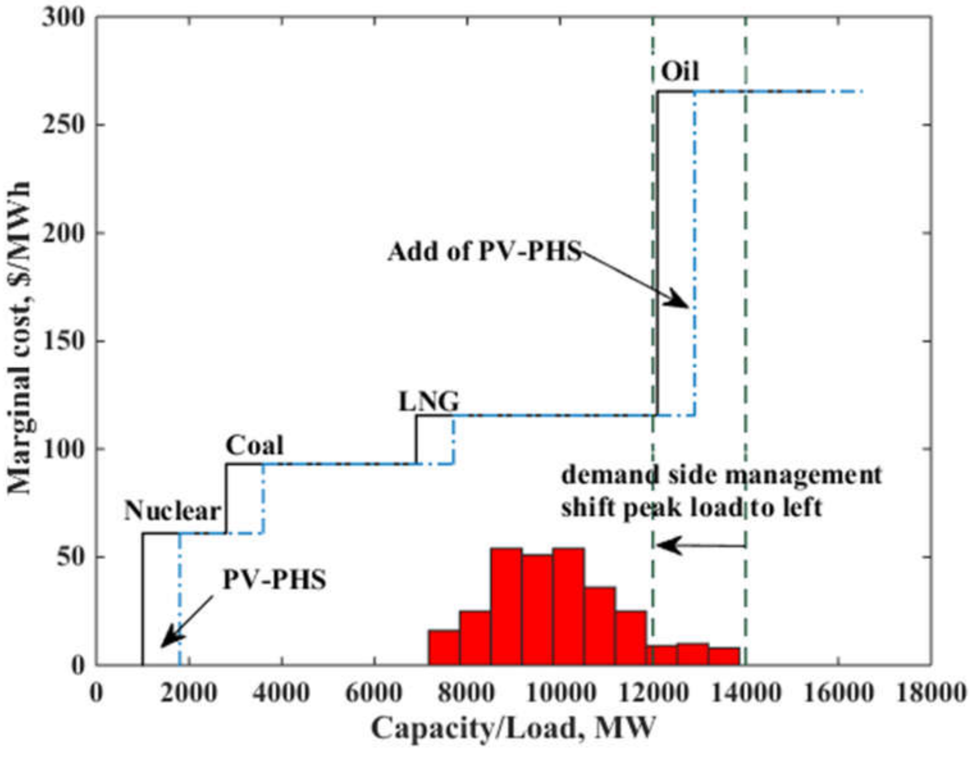


Fig.5-49. Merit order curve and peak shave effects of demand side management on power supply system

5.7 Summary

For developing sustainable and reliable power supply system, high efficiency appliances and integrated distributed power resources in demand side are expected to be important resources of future power supply system. This chapter investigated their cost saving and environmental benefits in residential sector, based on applications in social demonstration projects in Kyushu, Japan, and examined the grid load leveling effects of scheduled efficient technologies from a bottom up approach. The main foundlings of this research can be summarized as follows:

1. Aggregated heat pump and V2G systems can effectively be used for grid peak load leveling, heat pump water heater can flexibly shift heating demand to the early morning to bottom up the grid valley load, daily power consumptions of heat pump vary from 4.0 kWh to 10.0 kWh over the year, generally range from 20%~45% of daily power consumption.. Scheduled V2G can effectively cover the night peak load via optimal discharging strategy.

2. Due to the limited heating demand, fuel cell hardly runs in its nominal output during summer period. Fuel cell contributes more to customer electricity load under larger heating demand, it can be used as reliable peak power resources independent of the weather condition. PV production coincides with the grid peak period in summer and presents high peak capacity credit, and PV generating ability shows great variations among days over a year.

3. Heat pump water heater will provide chances to reduce CO2 emission 0.40 kg/(kW·day) via reducing fuel consumption, EV system with 2.5 kW charging capacity produces around 3.2 $/day profit through replacing gasoline consumption, and achieves economic benefits within 6 years.. Heat pump water heater system present a relative longer payback period (10 years) under current energy market, the feasibility of the on-site cogeneration system may still highly depends on the access to capacity subsidies under current energy market in Japan, despite its higher CO2 reduction, 1.76 kg/(kW·day).

4. Different technologies shows different roles in load leveling, optimal mix and coordinate management of installed technologies in demand side are important to local or community energy system, considering the feature and effectiveness of high efficiency technology. Policymaker need to understand the timing of this transition in order to detect load pattern changes for the technology mix plan

Analysis results found that aggregated high efficiency technologies can not only help the grid regulation but also reduce the social carbon emission. Higher initial investment is perhaps the most serious obstacle for preferences of high efficiency technologies in demand side. When the home appliances or on-site generator were scheduled for grid load regulation, financial incentive for customers to shoulder part of capacity cost may be favorable for the wider uptake of high efficiency technologies. Government-led, customer participation and business-driven is expected to become the main features in sustainable development of smart community energy system.

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Chapter 6

MARKET INNOVATION AND SUGGESTIONS

CHAPTER SIX: MARKET INNOVATION AND SUGGESTIONS

Increasing use of integrated renewable energy sources with variable output, such as solar photovoltaic, calls for smart grids that effectively manage flexible loads and energy storage. Incentive policy, technology innovation and consumer awareness provide opportunities for offsetting these effects through energy conservation and uptake of high efficient appliances. Real time communication and cooperation between customers, embedded controls in flexible appliances, and the central utility is important. This chapter mainly investigates the performances of price-based response, aims at shifting load usage during peak period. Meanwhile, based on estimated effects of efficient appliances, provides the market incentive implications for behavioral change in consumer habit.

6.1 Experience from social demonstration project (plant side management)

6.1.1 Price-based response research

To our knowledge, several studies [1-7] indicate that optimal price-based demand response strategies have great potential in maintaining the reliability and adequacy of power supply system, mainly through peak cutting and load leveling. Dynamic price program has got increasing attentions as an application on electricity market among different customers at district or national level,[Herter, McAuliffe [1], Jang, Eom [4], Wang, Fang [7], Lin, Wang [8]]. Benefits have been identified with both of these supplier and customer sides. For example peak demand cutting can decrease the need for output from high cost peak-meet generators, the potential bill saving for the customer via shifting pattern of electricity consumption. Meanwhile, customer services could be improved through enhancing reliability of the electrical system. [Herter, McAuliffe [1], Herter [5]] investigated the implementation of CPP tariffs in California, USA. They summarized the response performances and influencing factors of the residential sector. Analysis result offered convincing evidence that residential customers could provide substantial contributions to retail demand response, household power usage reduced 25.0% during five-hour critical period under high temperature. In addition, findings of CPP events exhibited that high-use customers respond more to kW reduction in critical periods than do low-use customers. Wang and Li [3] analyzed CPP event for manufacturing applications, modelled and compared both CPP and TOU electricity rate prices to gain more accurate knowledge regarding annual electric costs and GHG emission productions. Industrial customers with production flexibility can save 30% cost by adopting a CPP event program, meanwhile contributing to reducing 5.63% GHG emission. Yalcintas, Hagen [9] stated that shifting work schedules of office buildings with one hour early can save the electricity cost by 1-3% through reducing energy usage during critical peak period, dynamic pricing tariff also allowed the customer to implement new saving measures to reduce costs, such as thermal storage system. Jang, Eom [4] investigated the demand responsiveness and learning effect of commercial and industrial businesses of the event based CPP program in Korean, the result showed that both industrial and commercial businesses were capable of cutting peak demand on CPP event program, customers tended to learn faster with CPP experience with greater financial motivation, the industrial sector showed higher average reduction of peak load than commercial sector and there were existing wide-ranging difference in demand responsiveness across business categories. Faria and Vale [6] did the network demand response simulation considers both price and load reduction caps for commercial and industrial customers, results found that customer's demand responsiveness depends on price elasticity of demand and electricity pricing tariff, the approach can determine the price varations for customers, meanwhile maintain the retailer's profit. Wang, Fang [7] simulated the effectiveness of RTP to balance daily electricity load and promote electricity conservation of residential sector in China, the household electricity time-use survey indicated RTP presented a potential in shifting domestic use from peak to off-peak period, results showed peak load can drop 26-37% and valley usage can increase 16-22%. Meanwhile, household were not equally sensitive to electricity price change, raising household dwellers' sensitive to the price signals could improve the price-based response effects. Lin, Wang [8] developed an agent-based model to investigate the energy saving potential of office building in China under different pricing mechanism, 14.2% energy saving could be achieved under CPP tariff, which showed an effective role in peak clipping. It also highlighted the importance of improving people's awareness of energy saving and refining their behaviors. Fotouhi Ghazvini, Soares [10] exhibited the possibility of household energy consumption schedule according to the dynamic pricing scheme under optimization-based HEMS environment in Portugal, simulation results exhibited a 29.5-31.55% cost saving of a smart household with electric vehicle and electric water heater by shifting the optimal load consumption.

6.1.2 Social dynamic price experiment in Kitakyushu

Despite extensive researches on various approaches to the price-based demand response, there is still a lack of understanding of customers' willingness to change consumption patterns in a real district scale based on real monitored data. In addition, the electricity saving potential in response to changes of electricity price may vary across types of customer. A better understanding of electricity price-based demand response from different types of customer through real data-driven investigation can provide more comprehensive and useful information for the policy makers or district utilities. This research will examines the performances of CPP event considering the electricity saving and load shaping effects among three representative groups of electricity customer, composed of commercial, office and residential consumers in the Kitakyushu Smart Community Project.

Local policy maker is encouraging electricity customers to participate more in district electricity supply-demand management. Critical peak pricing program is applied for changing the behaviors of electricity customers under emergency status (significant change in the amount of renewable energy, significant fluctuations in electricity demand and peak load pressure), which can be announced and implemented in real time. It also aims at stabilizing frequency and voltage fluctuations of district grid within a certain range after introducing renewable energy sources on a large scale.

6.1.2.1 Network structure of price-based demand response

Digital communication technologies implemented among energy management system (EMS) enable the functionality of demand response based on dynamic electricity price scheme. Cluster energy management system (CEMS) and smart meters, which are the main communication tools in this demonstration project, as a means to 'discover/share/utilize' power resources and information within the community. With the real-time communication between CEMS and the smart meter, CEMS platform automated smart meter reading and sharing information from home energy management system (HEMS), factory energy management system (FEMS) and building energy management system (BEMS). Specifically, aims at establishing a system in which actions of citizens and businesses that not only produce profits for themselves would also contribute to community energy management, mainly through 'aggregating/visualizing' community energy information and introducing dynamic price in time. Those technique and management stategies aim at driving citizens and business to 'think' and 'participate' more in the district power system management. The research objectives of CPP social experiment involve 46 public buildings and 230 households, all CPP participations equiped with smart energy management system. Fig.6-1 shows the detail network and operational processes of price-based demand response, Solid line presents the electrical power flow, dot line presents the information flow consisting of real-time electricity price signal and power consumption, CEMS can send notification of power price, and exchange power consumption information with customers thorugh bi-directional communication network. The smart meters provide the chance of reveling energy consumption in real-time for utilities and customers, indoor indicator displays the dynamic price information from CEMS and induces the consumers to schedule optimal energy consumption. The introductions of BEMS and HEMS enable the customers to control the operations of electric appliances within the buildings corresponding to the real-time visualization, which can help the customers to form an energy saving habit.

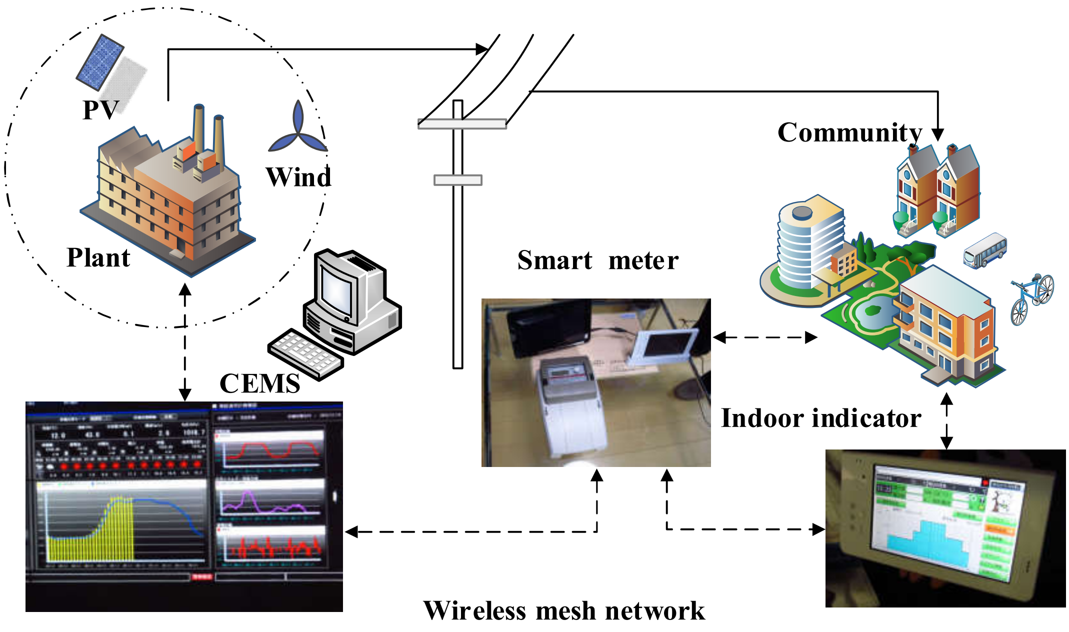


Fig.6-1. Overall structure of the Kitakyushu smart community network

6.1.2.2 Structure design of CPP program

The structure of the designed dynamic electricity price in the Kitakyushu demonstration project is a mixture of the TOU and CPP events. The prices and peak periods of TOU varied based on the seasons and the day of the week, time based pricing blocks of on-, mid- and off-peak periods are kept unchanged. In order to stabilize loads and ensure a reliable supply-demand balance in the demonstration district, the power rate price structure of CPP event is designed by imposing a prespecified high rate price at 30 minutes interval, which aims at encouraging customers to reduce electricity consumption during peak periods for specified weekdays in summer. Detail structures of the CPP event programs for non-residential and residential customers are shown in Fig.6-2 & 6-3. In the community scale, from 1:00 pm to 5:00 pm on weekdays is generally a high occurrence period of district peak grid load. Prices for CPP events can be 5-6 times as much as its normal TOU level to reflect the marginal cost of local eletricity generation. The price structures of CPP and TOU for types of customer show an obvious difference. For non-residential sector, parts of CPPs price may be lower than TOU, parts of CPPs price can be 2-5 time as much as the value of the TOU event. For residential customers, the power rate price of CPPs is determined by multiplying a coefficient based on the price level of the TOU program and the power rate price of each CPP event remains constant during the defined peak period.

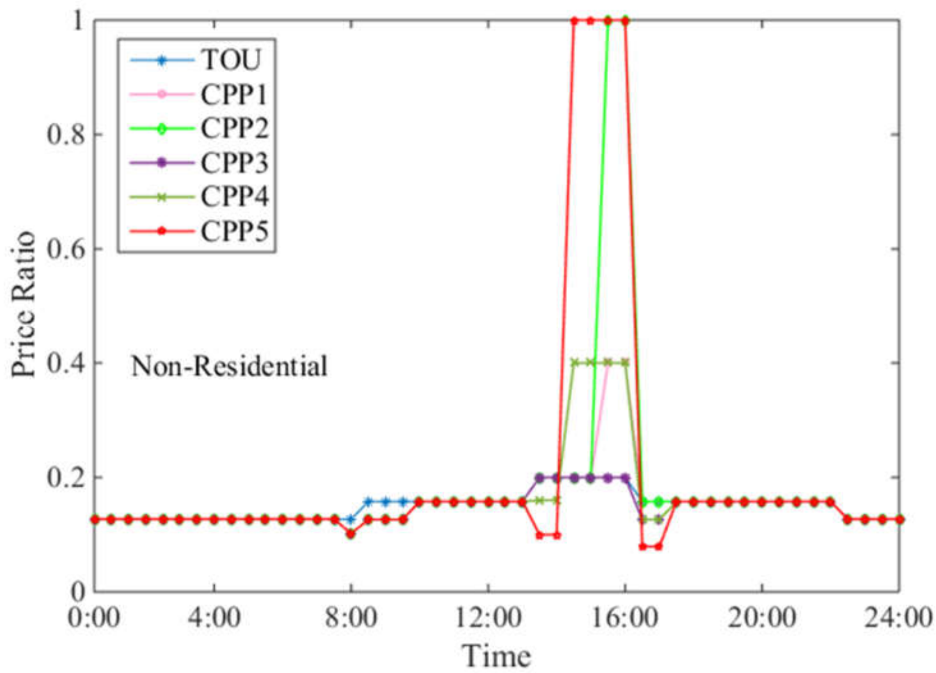


Fig.6-2. Rate design of CPP programs for non-residential in smart community project

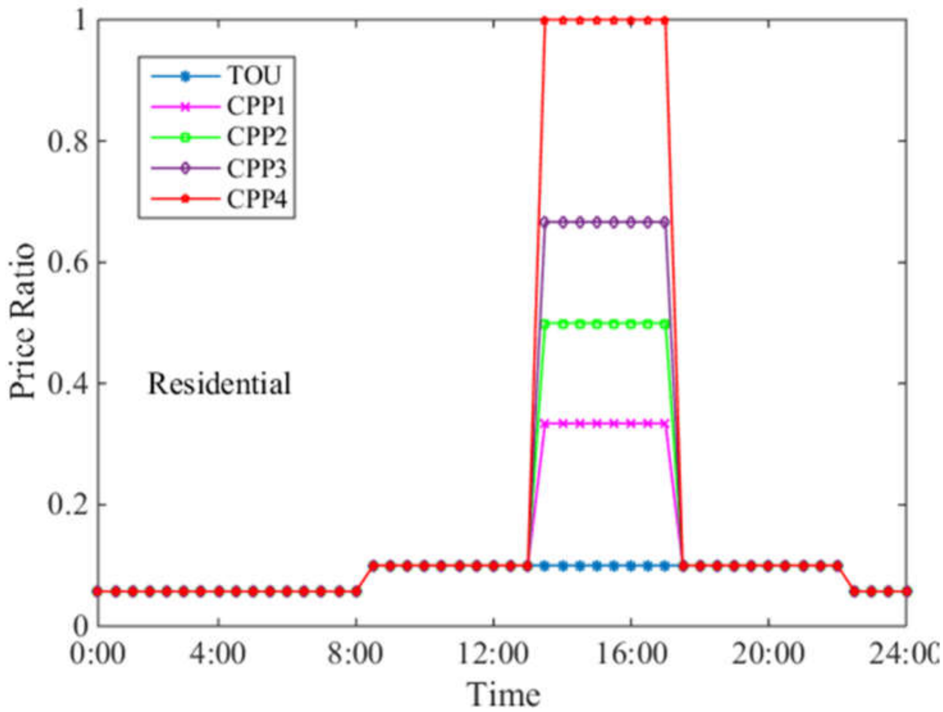


Fig.6-3. Rate design of CPP programs for residential customers in smart community project

6.1.3 Data source

As evidenced in many empirical studies, consumer's decision to switch to a time-variable power rate prices depends not only on the cost difference between CPP and TOU events, but also on the consumer's ability and willingness to change consumption patterns responding to the changes in marginal electricity price. In addition, load flexibility is closely related to the load consumption patterns of different customers. The CPP experiment events were conducted in various types of consumer located in the Kitakyushu Smart Community, Higashida District. Those voluntary participants consist of small-, medium- and large- commercial or office buildings, hotel, hospital small-industrial and residential households. In this research, we mainly report the performances of dynamic price demonstrations of general public office, commercial and household. From the viewpoint of aggregated group level, we will investigate the performances of dynamic price event for three main types of customer, group numbers of commercial, office and household building are 16, 15 and 50 respectively. This CPP experiment period lasts from 2011 to 2014, there is a nationwide electricity saving campaign during 2012 in response to the thought of tight power supply-demand scenario after 2011 Great East Earthquake, which may affect the power consumption patterns of customer. Considering the reliability and integrity, the selected experiment data is based on history monitored data in June and August 2013, which is the main occurrence domain of district grid peak period.

According to the received climate data and operation infromation from BEMS/HEMS, CPP event will be triggered based on forecasted scenarios of power supply-demand scenario and outdoor temperature. CPP levels from 2 to 5 would be chosen randomly among weekdays when predicted temperature is above 30^{o}C for the CPP event days. CEMS can announce power rate price table of impending CPP events to the customers before the event day, and notify the consumers again two hours ahead of events take place via message service. These CPP event days are limited to the weekday and non-holiday in July and August 2013. Table 6-1 summarizes the implemented results for each type of customer in this community.

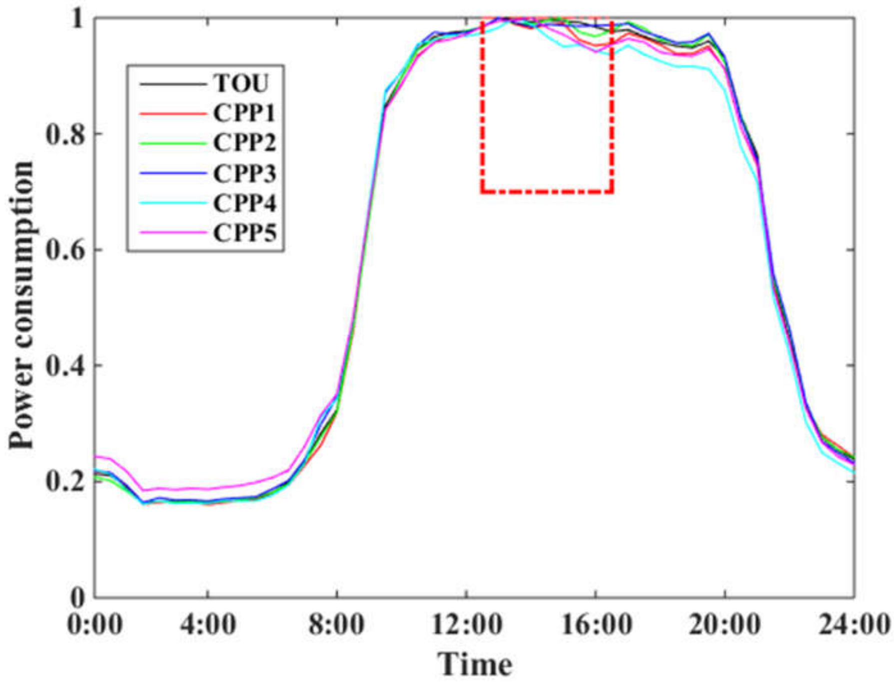
Table 6-1 Number of CPPs and TOU event days among customers (weekdays in July and August 2013)

Month	**July**			**August**		
Customer type	**commercial**	**office**	**residential**	**commercial**	**office**	**residential**
TOU	16	17	3	8	12	3
CPP1	2	2	4	3	3	4
CPP2	2	2	5	3	3	5
CPP3	1	1	5	4	4	5
CPP4	0	0	5	2	0	5
CPP5	1	0	0	2	0	0

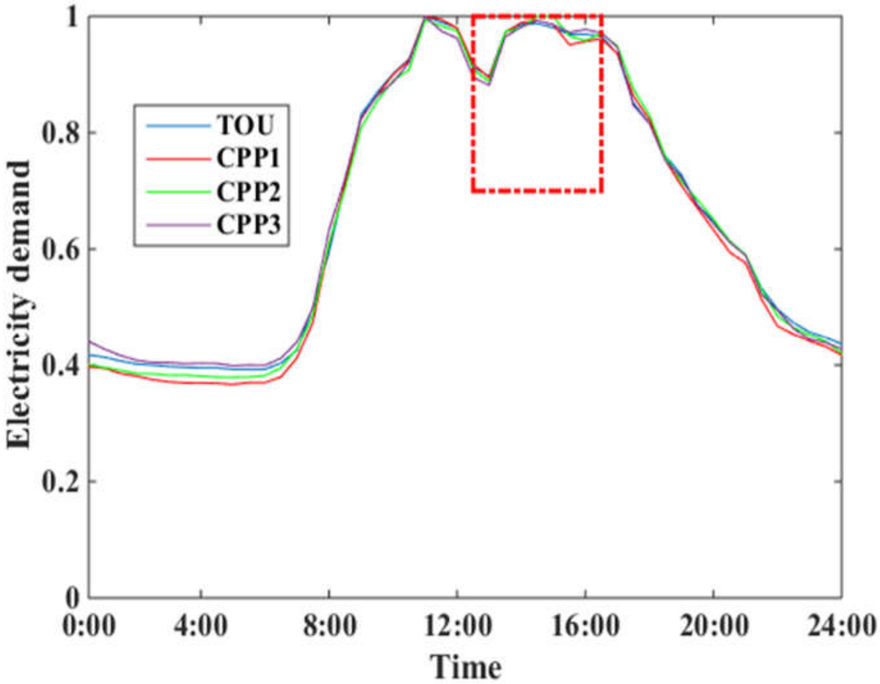
6.1.4 Analysis and result

The structure and implementation of CPP event programs were designed according to the characteristics of local power demand curve, which was a joint contributions from various types of customer. In the following part we will estimate the responsiveness of this dynamic price program, mainly through evaluating load shaping and power saving effects for different types of customer, consisting of commercial, office and residential. Firstly, we calculated their daily load patterns by averaging the electricity demand at 30 minute intervals between days of the TOU and each CPP event.

(a) Commercial



(b) Office



(c) Residential

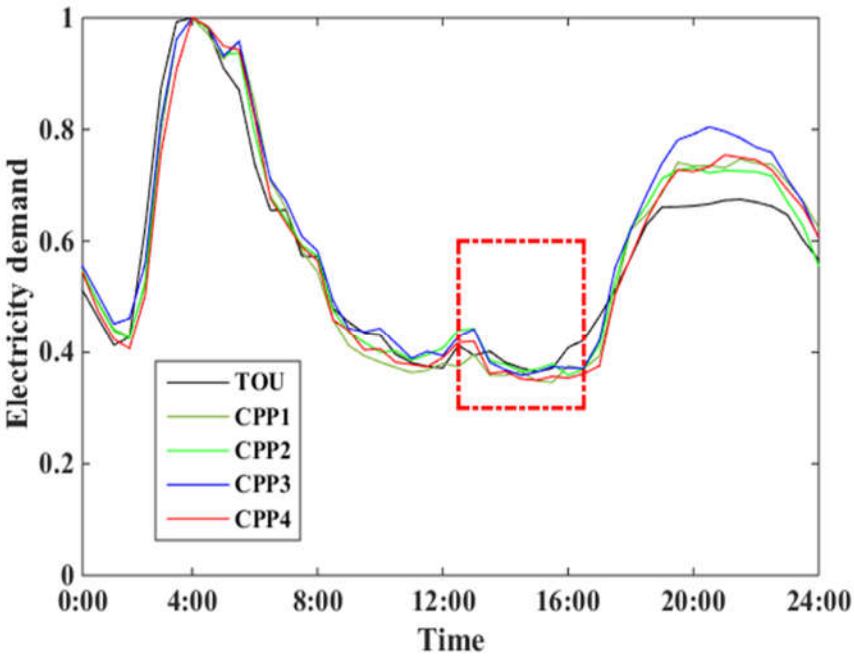
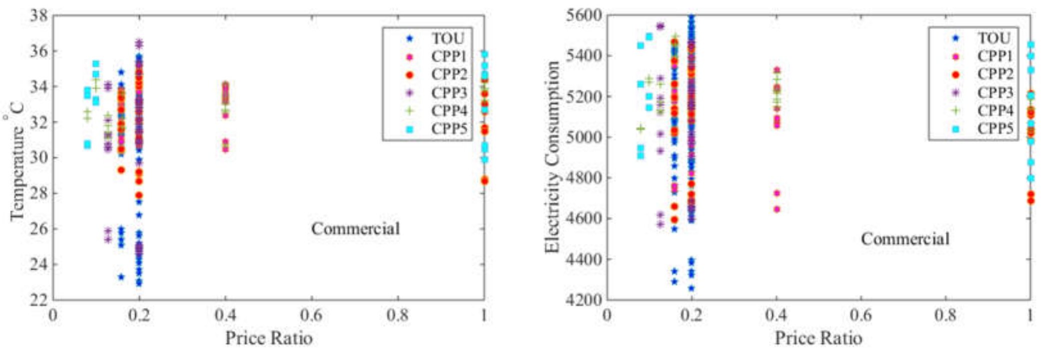


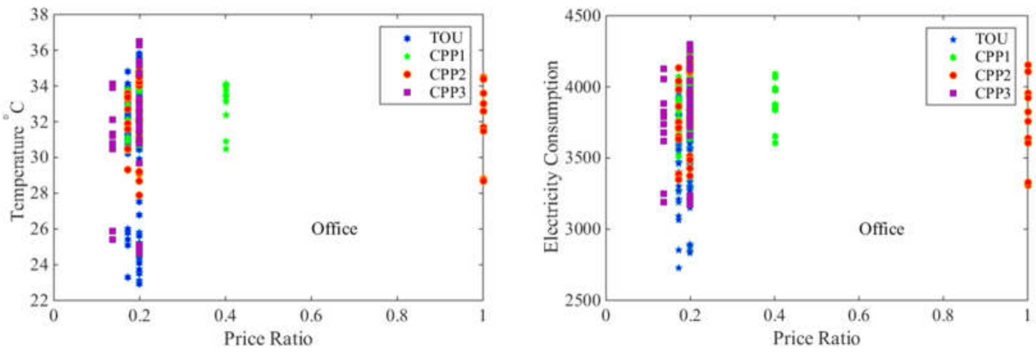
Fig.6-4 Comparison of demand curves for customers under the dynamic pricing program (TOU and CPPs)

Fig.6-4 (a-c) shows the comparisons of daily demand curves (daily variable value is normalized by dividing its maximum value) between the TOU and CPP events for each group of customer. Red box represents the designed peak period domain where CPP events take place. The off peak, on peak, critical peak periods and load variations in different types of customer can be clearly seen. Electricity consumption patterns of customers show an obvious differences that each customer has its own daily electricity usage pattern and preference. It is possible to confirm that daily demand curves of CPPs have been shaped among customers during the peak period. The electricity demand of commercial customer experiences a sharply increasing from around 8:00 am, then it experiences a relative flatten peak period lasts from around 10:00 am to 8:00 pm. We can see a clear reduction in power consumption after the occurrences of CPP4 and CPP5, such changes in demand curve can last till 8:00 pm, which indicates that the impact of CPP can excess the period of the event takes place. Power rate price of CPP3 is same with TOU from 1:00 pm to 3:30 pm, then there is a slight drop in power rate price after 4:00 pm. As a result, CPP3 shows a similar load pattern with TOU condition. Therefore, it is possible to confirm that the electricity saving potential varies across designed power rate prices. Office building group mainly experiences its peak period from around 10:00 am to 5:00 pm, there is an electricity demand drop from around 12:00 am to 1:00 pm as shown in Fig.6-4 (b), which may cause by the break for rest. Compared with TOU and CPP3, we can observe a behavior of weakly electricity demand reduction from 3:00 pm to 4:00 pm under CPP2 and CPP1 event, where the power rate price has been adjusted to a relatively high level. Fig.6-4 (c) presents electricity demand curves of residential customer, it is noteworthy that the period of CPP event is not consistent with residential peak electricity demand domains, which are mainly located in the early morning or evening. As observed, electricity demands during the CPP event period is generally smaller than TOU scenario that the curve of the TOU is mostly above the CPPs' curves. However, the electricity saving potential is hard to be determined corresponding to the power rate prices across the four CPP events. In addition, under the specific CPP event the residential load reduction performances are different during the period of CPP programs take place.

(a) Commercial



(b) Office



(c) Residential

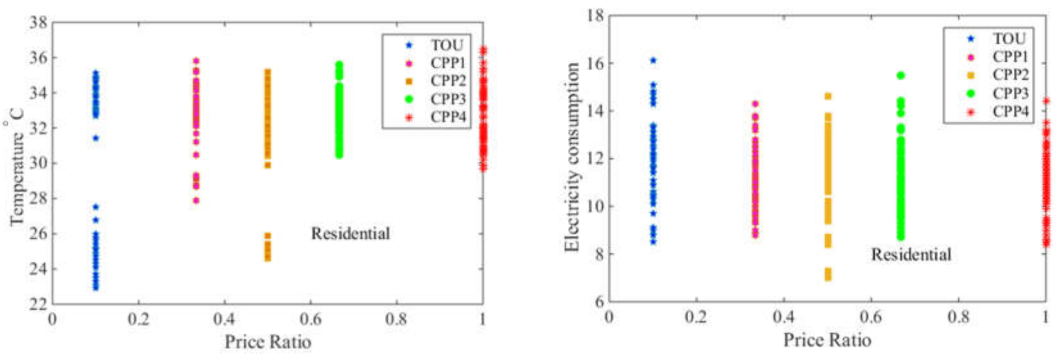
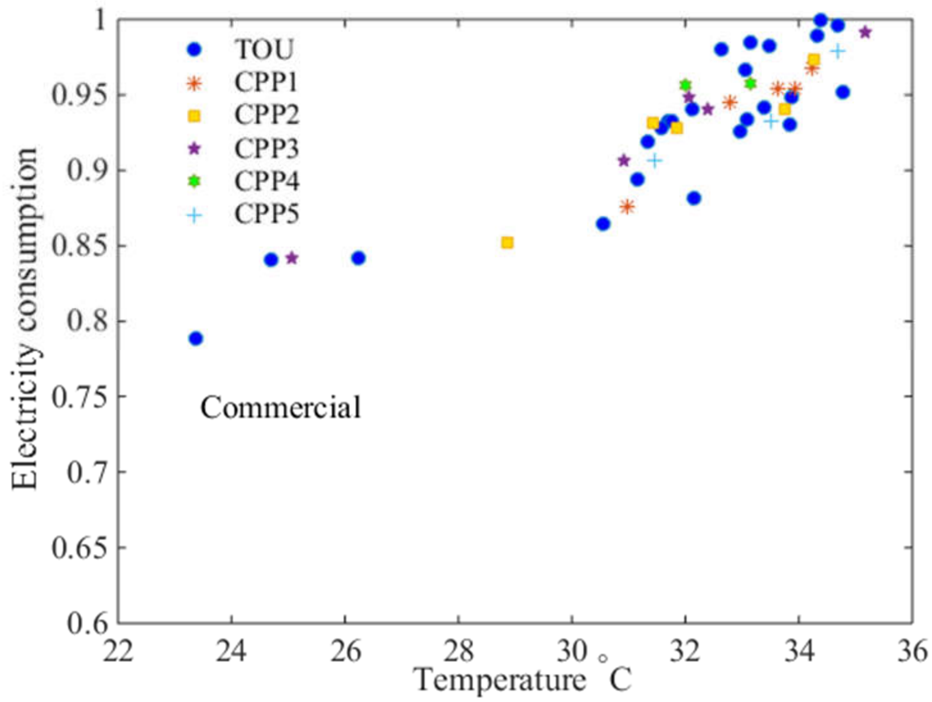


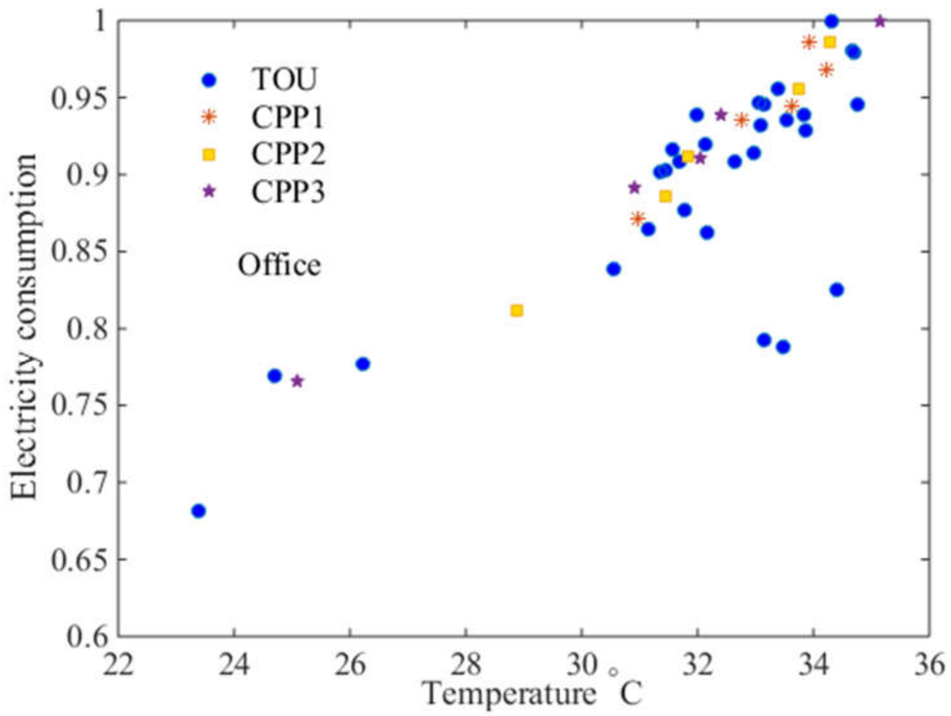
Fig.6-5. Scatter distributions of temperature and electricity consumption during event period under TOU and CPP events

It is expected that electricity consumption has a close relationship to temperature and electricity price. One main objective of CPP experiment is to reduce the peak demand via changing electricity price in response to the forecasted weather temperature and supply-demand scenario. During CPP days, type of CPPs was randomly selected and power rate prices among types of customer are different, therefore we normalized the electricity prices of the TOU and CPP events by dividing its own maximum value. Distributions of electricity consumption of the building group level under different price ratios from 1:00 pm to 5:00 pm are shown in Fig.6-5. We can clearly see that there is an increasing trend of electricity demand with the increasing outdoor temperature, electricity demand and temperature show similar distributions under corresponding price ratios. In commercial part Fig.6-5 (a), the minimum temperature of CPP1, CPP2, CPP4 and CPP5 events at higher price ratio (over 0.2) is generally above 30 °C. The maximum electricity consumptions are mainly located in price ratio range of 0.1-0.2 under high temperature during TOU and CPP3 events. We can generally confirm the success of the implemented dynamic price program. The high temperatures of the TOU and CPP5 events are nearly the same, however, the electricity consumption of CPP5 at a higher price ratio is less compared with TOU event. In office sector Fig.6-5 (b), similar with commercial customers temperatures of CPP1 and CPP2 events that feature with a higher price ratio are generally above 30 °C. Compared with the condition of TOU event, designed power rate price of CPP3 is generally same or slightly lower during defined peak period. Electricity consumption of CPP3 at a price ratio 0.2 features with the highest electricity consumption. The maximum temperatures of CPP1 and CPP2 events are almost same, however it is hardly to see the reduction in electricity consumption when we increase the price ratio from 0.4 (CPP1) to 1.0 (CPP2). Fig.6-5 (c) shows the detail distributions of temperature and electricity consumption in the aggregated residential group. The maximum temperature of the TOU is lower than CPP1 and the minimum temperature of CPP1 is higher than condition of the TOU. When price ratio ranges from 0.1 (TOU) to 0.33 (CPP1), we can see that maximum electricity demand of CPP1 is lower in comparison with the TOU, and the minimum electricity demands of the TOU and CPP1 are nearly equal, which can confirm the effectiveness in power saving from the implementation of this CPP event scheme. When we vary the levels of household CPP events from 1 to 4, there is a tendency to show that the higher price, the greater potential in cutting total electricity loads of the event periods. The overall distributions confirm that CPP events with a higher power rate price play an effective role in decreasing electricity consumption of residential group.

(a) Commercial



(b) Office



(c) Residential

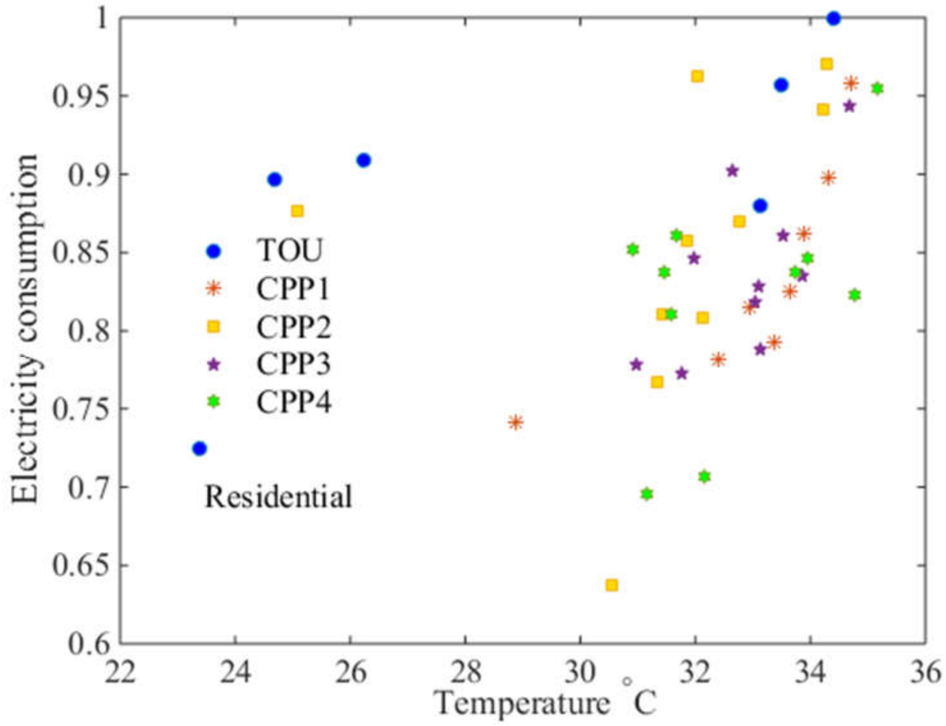
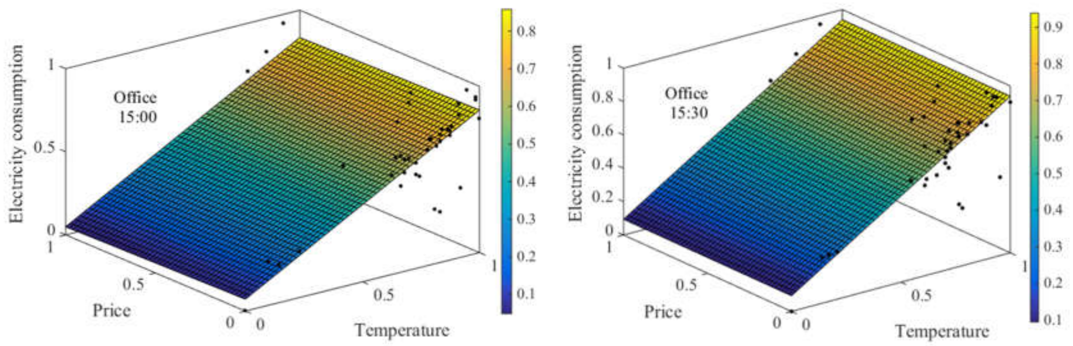


Fig.6-6. Variations of total electricity consumption of TOU and CPPs events days, event period lasts from 1:00 pm to 5:00 pm

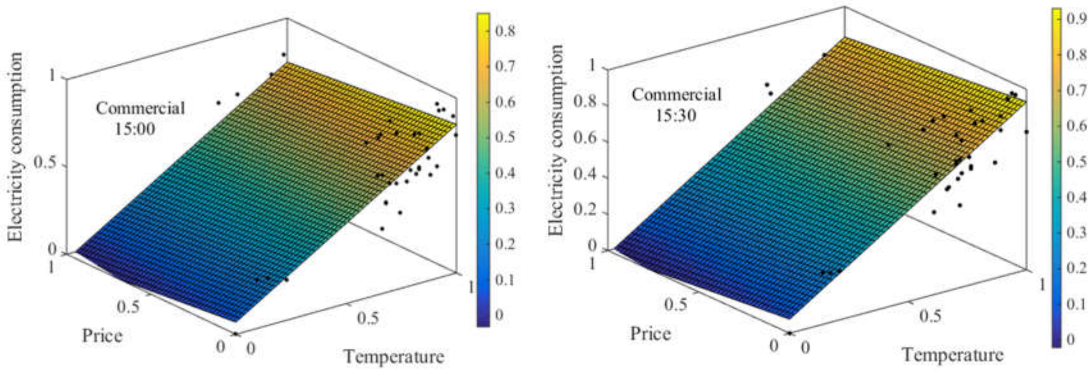
CPP events affect the electricity consumption during the defined peak period from 1:00 pm to 5:00 pm, the values of the electricity consumption are normalized into 0-1 ranges for each group among the TOU and CPP event days. Fig.6-6. (a)-(c) show the distributions of the power consumptions corresponding to the average outdoor temperature. Total power consumptions during the period show an increasing trend with higher average temperature. The maximum values for each group generally happen under TOU event days, it indicates the ability of CPP events in peak load cutting. In comparison with TOU event at nearly temperature level, we can clearly see the reduction of the total power consumption in commercial and residential sectors under the CPP event program. The electricity saving effects under CPP events in the commercial sector can be confirmed when the average temperature is over 32 ºC, power saving may be contributed by optimal load control of air conditioning system. For the residential consumer, the higher of the electricity price, the greater power saving effect can be seen corresponding to the nearly temperature levels.

As shown in Fig.6-5&6-6, the electricity consumption has a strong correlation with power rate price and temperature. In addition, the electricity usage patterns of customers strongly depend on time interval *h* (13:00, 13:30,..., 16:30) during the main CPP period. Considering the electricity tariff structure, we select the specific data including temperature, electricity price and electricity demand to analyze the performances of CPP events, at the fixed time 15:00 and 15:30, where the power rate price shows obvious variations among these weekdays as shown in Fig.6-3&6-4. The period includes 44 weekdays that composed of the TOU and CPP events. A time based multiple linear regression model is employed to investigate the influencing factors, and examine the effectiveness of price-based demand response from types of electricity customer. The regression model for electricity customers at a specific time *i* can be written as:

(a) Office



(b) Commercial



(c) Residential

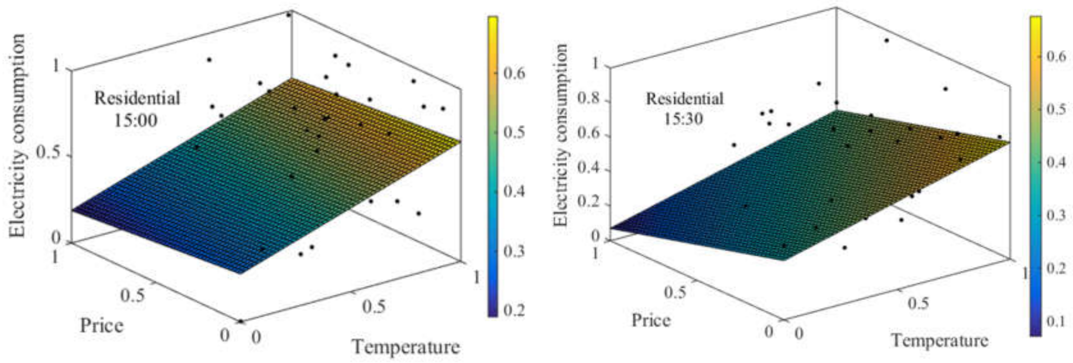


Fig.6-7. Planes of the regression model for types of customer under the dynamic price program, 15:00 left, 15:30 right

$$x_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \quad \text{Eq.7-1}$$

$$y_i = \frac{y_i - y_{\min}}{y_{\max} - y_{\min}} \quad \text{Eq.7-2}$$

$$f(x,y)_i = \frac{f(x,y)_i - f(x,y)_{\min}}{f(x,y)_{\max} - f(x,y)_{\min}} \quad \text{Eq.7-3}$$

$$f(x,y) = p00 + p10 \cdot x + p01 \cdot y \quad \text{Eq.7-4}$$

Where, *x* presents the outdoor temperature, *y* presents the power rate price, $f(x,y)$ is the electricity consumption. Considering the different value ranges of variables, according to Eq.1-3 we normalized the values for all attributes into the range of 0-1 respectively, in the normalization procedure, the variables *min* and *max* are the smallest and largest values in the dataset, *i* presents different weekdays. Table 6-2 summarizes the results of the regression coefficients and goodness of fit for each consumer group. Coefficient p00 presents the mean response for $f(x,y)$, when all the predictors *x*, *y* are all zeros. These coefficients p10 and p01 present the changes in the mean response, $f(x,y)$ per unit increase in the associated predictor variables. For example, p10 presents the change in mean electricity demand response per unit increase to temperature when the power rate price is held constant. Confidence and prediction bounds define the lower and upper values of the associated interval, we calculate a 95% prediction interval between each value of the days consist of the TOU and CPP event programs. This interval indicates that we have a 95% chance that the new observation is actually contained within the lower and upper prediction bounds.

Table 6 -2 Regression coefficients and goodness of fit for each type of customer

Coefficients		p00		p10		p01		SSE	R-square
Time	Type	Value	Confidence	Value	Confidence	Value	Confidence	Value	Value
15:00	Commercial	0.070	(-0.051,	0.78	(0.62, 0.93)	-0.10	(-0.20, -	0.55	0.71
	Office	0.071	(-0.064,	0.79	(0.61, 0.96)	0.022	(-0.10, 0.15)	0.69	0.67
	Residential	0.28	(0.0021,	0.42	(0.053, 0.78)	-0.089	(-0.34, 0.16)	2.8	0.12
15:30	Commercial	0.078	(-0.039,	0.85	(0.70, 1.0)	-0.10	(-0.19, -	0.51	0.74
	Office	0.091	(-0.048,	0.84	(0.66, 1.0)	0.0051	(-0.12, 0.13)	0.72	0.72
	Residential	0.34	(0.13, 0.55)	0.33	(0.039, 0.63)	-0.27	(-0.46, -0.080)	1.6	0.20

In the case of two predictors (electricity rate price and temperature), the estimated regression equation will yield the regression planes for each type of customer as shown in Fig.7. Scatter represents the distribution of sample points. For each observation of electricity consumption, the variation in real and predicted values can be described as:

$$f(x,y) = f(\hat{x},y) + \varepsilon \quad \text{Eq.7-5}$$

Based on Eq.4 we can make a prediction for each observed data point, regression examination in Table 6-2 shows that mean response effects vary across the types of customer. The residual error ε in Eq.5 is the difference between predicted value $f(\hat{x},y)$ and true value $f(x,y)$ of variable, SSE is the sum of squared errors (ε^2). The R - square is a statistical measure of how close the data are in the fitted regression line, it can range between 0-1, and the higher its value the more accurate the regression models. As shown in Fig.6-7 (a)-(c) electricity consumptions of all customers will rise with increasing temperature, the regression coefficients p10 for commercial and residential are mainly located in negative ranges, indicating the reciprocal relationship between power load and power rate price.

Office and commercial groups are more sensitive to per increase in temperature (coefficient p10). From the empirical perspective of engineering, it may be caused by the great electricity consumption proportion from the air conditioning in summer. Electricity consumption of office sector shows a weak correlation with power rate price, the response effects of CPP events appear negligible, the value of p10 is close to 0. The mean regression values p01 for the commercial sector are negative, which indicates that consumers participate in electricity saving corresponding to the increase of electricity price, and price-based response effects are nearly same (p01, -0.10) at time 15:00 and 15:30. In addition, part of the commercial participants with large area account for a large ratio of total power consumption in the commercial sector, it is relatively easy to control and adjust the electricity load of air conditioning system.

The residential voluntary customer features with relatively low daily power consumption compared with the commercial and office customer. The aggregated group tends to respond more to the changes of electricity price, which shows an obvious decreasing trend of electricity consumption in the regression plane corresponding to per increase in power rate price at 15:30. Regression planes in Fig.6-7 (c) also show that there is less load reduction at 15:00 than 15:30 to the increase in electricity price. In the residential sector, responsive effects may vary significantly according to the same changes in electricity price at different time of the dynamic pricing program takes place, it highly depend on their own preference to change their electricity usage pattern.

6.2 Implications for policy maker (demand side management)

Energy efficiency contributes to the achievement of a sustainable future because, and improves the social welfare through reducing carbon emission. High initial capital investment may be the main barriers to promote the energy efficiency products in demand side. Incentive schemes such as subsidies, specific price scheme are widely used to promote energy efficient appliances. This section presents a methodology for optimal design of incentive schemes considering their performance, encouraging consumers to purchase energy efficient appliances, particularly when consumers participate in coordinate self-regulation or load pattern shift.

Some papers [2, 11-14] have explored the effectiveness of taxes, dynamic price and subsidies for promoting energy efficiency appliances with respect to policy goals such as efficiency, effectiveness and implementation feasibility. Ref [15] points that distributed energy resources and novel uses of electric energy by end users provide opportunity for more active participation in demand side, highlights future reforms of electricity market designs. Ref [16] examines how green subsidies affect purchase of new hybrid electric vehicles, green subsidies aid the environment and bring potential benefits to consumers. Ref [17] highlights uncertainty in benefits and cost lead delay in investment timing, policy incentives that reduce uncertainty in returns from solar PV are most effective. Ref [11] presents that policy goals could concern emission reduction targets, achieving a certain number of efficient appliances or increasing the proportion of efficient appliances to a certain level. Ref [18] analyzed potential effects of price based mechanism for residential demand side management, price based response program has a role in shifting usage pattern. Ref [19] states that environmental awareness, social interaction and customer preference have significant effect on purchase energy efficient appliances, incentive program and government efforts are important to encourage people to purchase more energy efficient appliances. Ref [20] designs subsidy programs focus on maximizing societal net benefits, capacity-based subsidy payments would substantially reduce the likelihood of negative electric market prices. A more thoughtful examination of the impact of subsidization program design on wholesale power market is long overdue.

6.2.1 Subsidy policy to thermal storage

For a time of use rate schedule, heat pump water heater operating domain mainly locates within the valley price period, gaining revenue for consumer with all electrification. For thermal storage tank on 370~460L, this volume rates are designed for meeting residential daily hot water usage. As shown in Fig.6-8, the daily estimated power consumptions of heat pump heater range from 2.6 kWh to 8.8 kWh, the variations have great relationship with daily heating load and weather conditions. Power consumption is higher in winter period due to the rise in thermal load and drop in COP of heat pump water heater system.

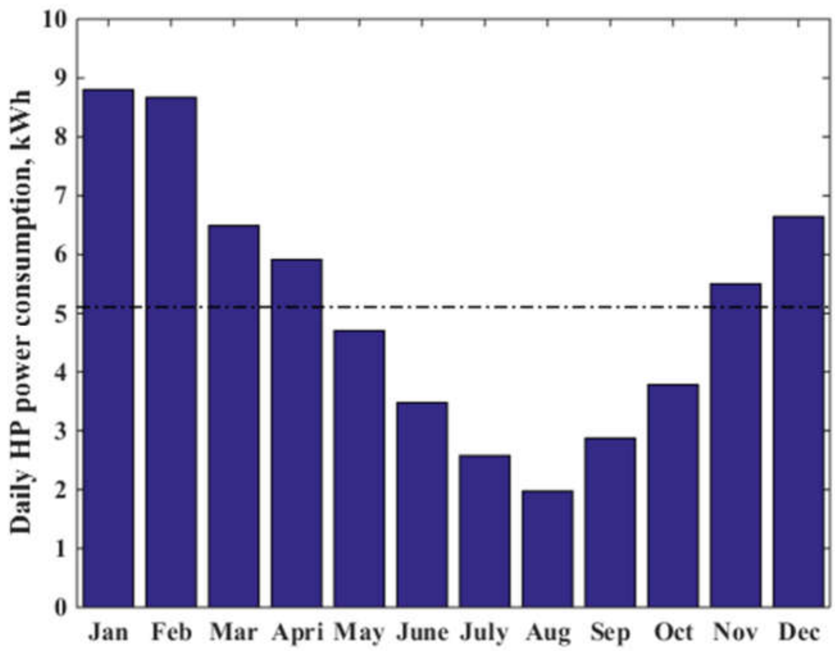


Fig.6-8. Variations of daily heat pump power consumption

General rule, lifespan of heat pump water heater lasts 10-12 years. According to the calculated result in section 6.1, consumer achieves the net profit until 11th year. Heat pump water heater system also provide the carbon emission reduction. Considering relative long payback period, relevant subsides or specific designed price schemes are essential for the consumer preference of heat pump water heater system, incentive its wide uptake.

Further increase in COP increase less in overall net profit, for the colder region the performance of heat pump system may change worse. It is estimated that the payback period may reduce from 10 years to 9 years when the annual overall COP rise from 3.4 to 4.0. Therefore, optimal designed valley price is essential to short the payback period. Meanwhile, wide utilization of heat pump during valley period can bottom up the grid valley load from aggregated form, benefiting the grid flexibility on daily basis.

7.2.2 Development of distributed generators

In sections 6.3 & 6.4, the economic performances of on-site generators are investigated in detail. Accompanying the decrease in capital cost, PV alone system can achieve the net revenue within 8 years under current feed-in tariff scheme without any subsidies to initial investment. Further drop in current feed-in tariff will enlarge the payback period. Optimal management strategies for enhancing local self-consumption is essential, such as optimal load shift and battery dispatch. Operating performance of residential fuel cell cogeneration system highly is limited to the simultaneously heating and power loads. Aggregated fuel cell can participate effectively in peak load shave during winter period. However, it contributes less during summer season limited to the lower heating demand. Overall energy efficiency of the cogeneration is higher (85%~90%), achieve promising carbon emission reduction. Meanwhile fuel cell output is independent on the climate condition, it show high reliability to participate in night peak load reduction in absence of PV generation. The effects of 500 thousand participation of proposed hybrid energy system described in Section 6.4 is shown in Fig.6-9, demand curve refers to grid load of Kyushu island.

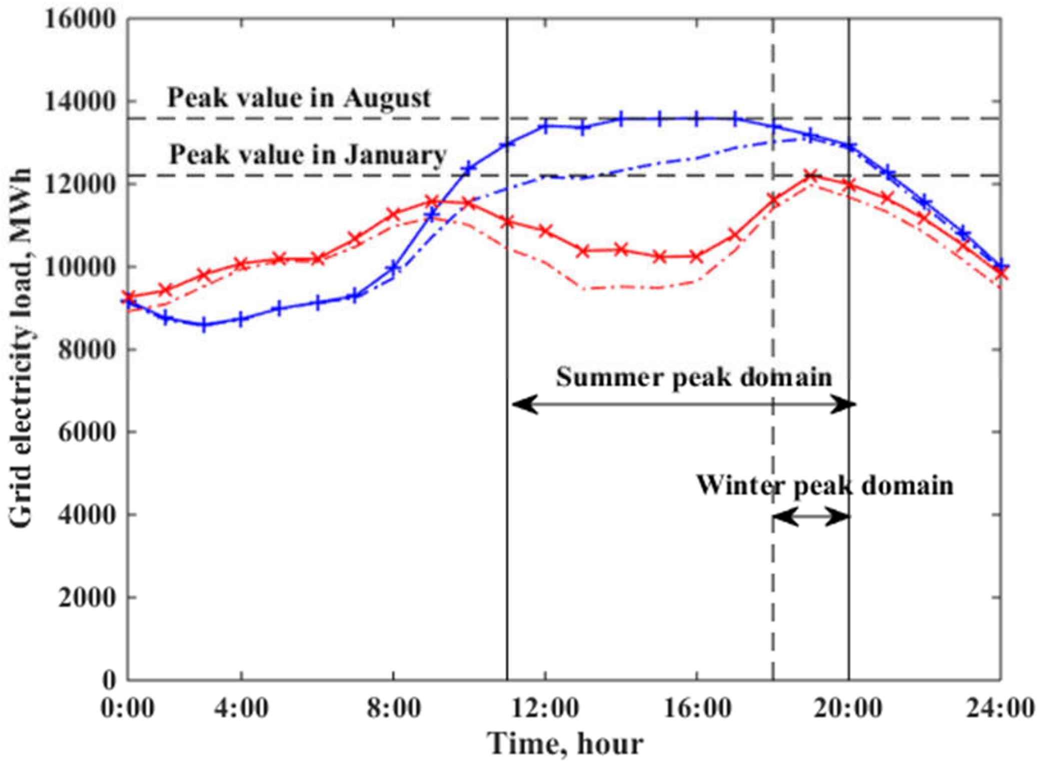


Fig.6-9. Grid load profiles and peak period domains, and adjusted load profiles with participation of 500 thousand ZEH in Section6.4.

Considering high initial capital investment in fuel cell, heavy cost burden is the main barrier for the consumer to adopt the cogeneration system in detached house. Considering potential social warfare from carbon emission reduction, subsidies to capital cost or optimal gas fuel cost scheme for residential cogeneration is essential to encourage consumer's purchase.

6.2.3 Incentive to power storage

Under current electricity market, incentive subsidy to battery unit is essential to shorten the payback period of the proposed grid-supporting power battery system, such as reduce reverse flow and grid load leveling.

HEMS controls electricity power of charge or discharge of battery storage and schedules the appliance in building, providing chance to increase self-consumption with increasing number of PV system in demand side, and minimizing electricity fee considering specific tariff structure. Meanwhile, aggregated uptake of battery can be seen as virtual power plant to stabilize grid load and serve as power resources. Therefore, the combination of feed-in tariff and incentivized self-consumption option are essential for effective utilization of distributed PV system.

In residential V2H system, optimal management strategy of battery installed in plug-in hybrid vehicle could be designed to be local power resources, charging/discharging schedule is important to utilize the battery storage to benefit the community energy system. Massive in-vehicle battery can be utilized to balance demand and supply in a grid.

Residential PV-battery system

The PV self-consumption ratio will increase by adding the battery, it can help reduce the electricity consumption cost, minimize the loss revenue from sold electricity when the FIT further decreases. Meanwhile the outcome influences of the proposed PV battery system may be attribute to both consumer and the power supplier. From the perspective of consumer, the implement of battery needs a high initial capital investment, reduce profit from sold PV generation. In addition, optimal control and management strategies on battery can shave peak load, smooth the demand curve and reduce transmission loss for the public grid in aggregated level. Therefore, a further cost drop or proper payment mechanism art between power and demand sides is essential to encourage the uptake preference of the grid-supporting PV battery system. Section 6.3 designs the PV-battery system aims at motivating residential customer to manage the battery flows, reducing imported electricity during peak period of the grid.

The payback periods of proposed PV-battery equal the net cost of customer to zero after the relevant incentives subsidy (initial capacity cost 400$/kWh , 800$/kWh), detail results regarding net present value are illustrated in Fig.6-8 &6-9. The feasibility and wide spread of proposed PV-battery system may highly depend on cooperative market mechanism between producers and consumers. Further drop in feed-in tariff will enlarge the payback period considering the future stricter feed-in limitation. As the decreasing trend in battery cost and feed-in tariff continue to decrease, the economic performance of proposed PV-battery system is expected to become more economical attractive in the coming years.

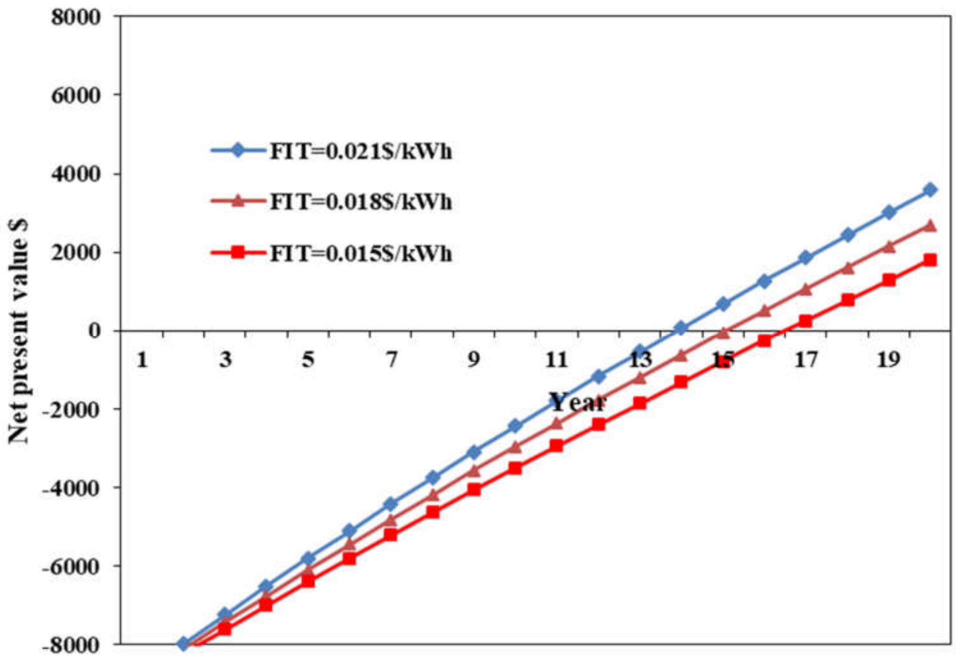


Fig.6-8. Net present value of residential 5 kWp PV and 3 kWh battery system, battery cost 800$/kWh

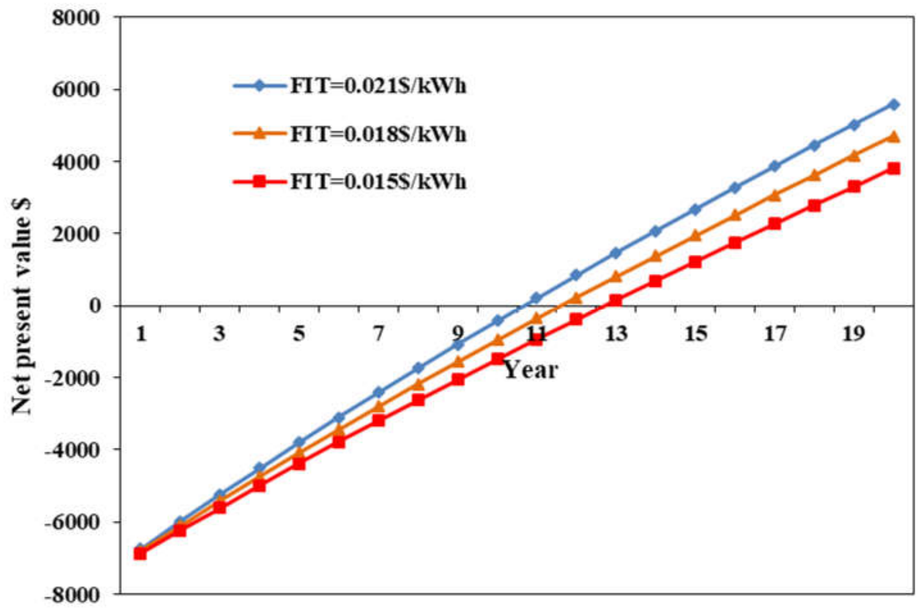


Fig.6-9. Net present value of residential 5 kWp PV and 3 kWh battery system, battery cost 400$/kWh

V2H system

EV provides a chance to replace gasoline for driving, reducing the carbon emission. V2H enable the plug-in battery to serve residential household as backup power out of grid. Benefit from price difference under time of use tariff scheme is less compared with fuel cost saving. It is reasonable to provide incentive subsidies to encourage the EV to participate in residential, community and micro grid energy management, through optimal management of battery charging/discharging schedule. Meanwhile, battery reduces reverse flows from distributed energy system, minimizing its impact to the grid. Li-ion battery still shows economic disadvantage due to its shorter lifespan compared with pump hydro storage system. However, the battery storage system shows more flexibility compared with central large-scale power storage system, community central control system can design optimal charging/discharging schedule to facility the local energy supply. In order to maximize social welfare, power market cooperation such as specific price scheme and incentive subsidy between consumer and utility is important.

6.2.4 Performance comparison of the high efficient technologies

Fig.6-10 presents the net present value of high efficient appliances, it is hard to achieve benefits for customer with PV-CHP hybrid system proposed in section 6.4, their economic feasibility o still highly depends on direct supported subsidies or adjustment in energy pricing, high initial investment is still the main obstacle to its wide development over coming decades. Heat pump water heater system can achieve net profit within its lifespan (12 years), but the payback period is longer than 10 years, proper subsidies or further capital cost drop may encourage the customer’s preference of Eco-cute. EV system achieves a promising net benefit within 10 years, due to the cost differences between electricity and gasoline.

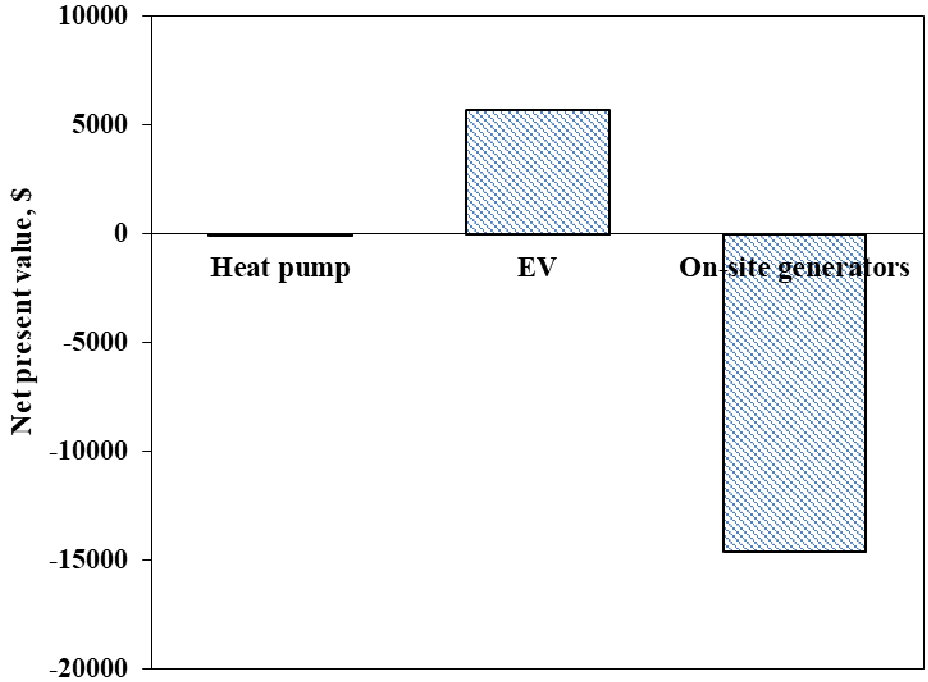


Fig.6-10. Net present value of high efficient technologies within 10 years from 2017 to 2027

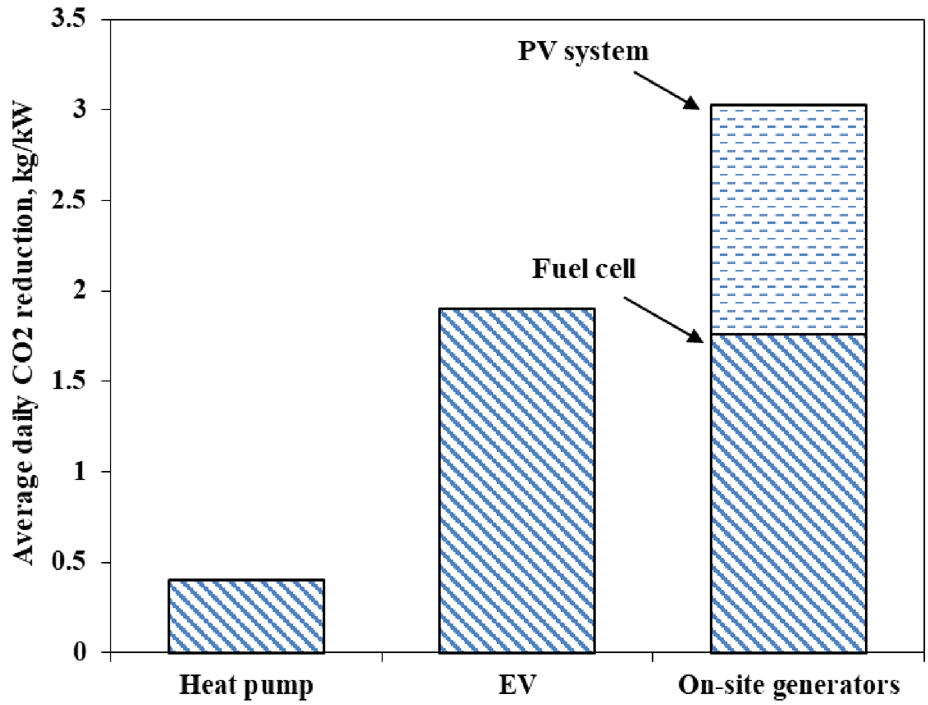


Fig.6-11. Comparison of various high efficiency technologies for average daily CO_2 reduction

Choose 85.0% thermal efficiency for conventional hot water boiler, annual overall COP of heat pump is 3.4, and assume the CO_2 emission factor of nature gas and gasoline are 2.29 kg/Nm3 and

2.32 kg/L, respectively, 0.483 kg/kWh CO_2 emission factor is chosen for imported power from Kyushu public grid. The annual average daily CO_2 emission reductions per capacity (kW) of high efficiency technologies were estimated as illustrated in Fig.6-11. Environmental benefits of heat pump and EV were achieved from the replaces of natural gas and gasoline consumptions. Emission reduction of on-site generators is attributed to PV production and recycled waste gas from fuel cell for heating demand.

6.3 Summary

From plant side perspective, section 6.1 provides the social experience from dynamic price based demand response, utilizes the monitored history data to analyze the demand response effects to the critical peak pricing event from types of customer in the Kitakyushu Smart Community demonstration project. The demand curves and changes of daily electricity consumption during the CPP event period are investigated in detail, including commercial, office and residential types. Corresponding to the power rate prices, the average demand curves and scatter distributions of the group-level electricity consumption offer convincing evidence that commercial and residential customers can effectively respond to the CPP event program. The demand curves also indicate that the effect of CPP program can overpass the periods that CPP events take place. However, electricity consumption saving and curve shape effect of office consumer group shows a weak correlation with the dynamic electricity price. The behaviors of change in daily electricity consumption curves can be obviously observed in commercial and residential sectors when the CPP event is triggered, the electricity saving effects during CPP event period are also confirmed. The CPP event is capable of shaping the electricity demand curve across types of customer, the demand reduction in residential sector during CPP period is greater when the power rate price is adjusted to a high level. The power saving effect in commercial sector generally happens when the outdoor temperature is high, which may be brought by activity or comfort based load control, such as air conditioning.

From demand side perspective, the integration of advanced electrical technologies in demand side can provide flexible power resources to the public grid in a decentralized way. Section 6.2 provides energy market policy implication for the development and integration of high efficient technologies based on corresponding demand side management effects, including battery, thermal tank storage and on-site generators. EV enables great potential to reduce the carbon emission via replacing gasoline, the economic feasibility of battery for power load management still highly depends on relevant policy incentive. Reasonable financial incentives for customers to shoulder part of capacity cost may enhance the wider uptake of grid-supporting high efficiency technologies. Direct subsidies to heat pump water heat system and cogeneration are essential for their wider development due to the high initial capital investment. Optimal mix and coordinate control of high efficient technologies enable customers to participate more in grid load leveling, considering their different features and roles.

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Chapter 7

CONCLUSION AND OUTLOOK

Conclusions

Real time power supply-demand balancing is a complex engineering, as the share of renewable energy resource in energy supply system is increasing, new challenges arise regarding grid integration. The shape and variability of electricity demand change significantly driven by economic growth and seasonal increasing indoor comfort requirement, demand side management is expected to provide potential grid flexibility. Decentralized energy planning is important to assist in realizing sustainable supply system. With increasing share of efficient power technologies installed in electrical distribution grid, their integration to the public grid needs to be planned similar to the integration of renewable energy resources. Therefore, modeling and optimization of sustainable power network should consider resources located in both of supply and demand sides.

For plant side optimization, feasibility study of virtual power plant is investigated based on the combined resources of supply and demand sides. Results present promising cost saving and social carbon emission reduction benefits based on cooperation between utilities and consumer. Increasing renewable-energy penetration level brings promising environmental benefit and energy self-sufficiency security at district level, however the variable renewable energy (VRE) differs from the conventional power supply technologies, integrated intermittent output from VRE poses various challenges for grid operation, actual market value of renewable energy drops due to curtailment considering grid flexibility. Storage system can play an effective role in promoting renewable utilization via absorbing excess generation, and release stored energy for peak shave, especially during mid-seasons. Combination of PV and PHS further decreases the output from medium plant generally reduces the overall electricity generating cost. Simulation result will inform the strategy for managing the grid flexibility requirements created by growing renewable energy. Provide meaningful insight for grid planner as they participate the growth of renewable energy resources and the strategies they should implement to meet flexibility requirement.

For demand side management, the buildings sector is facing a trend towards decentralized, more efficient technologies to cover the electrical or heating loads. Decentralized buildings can be part of the solution in the future smart energy grid, aggregated buildings will be both user and producer of energy. However, high initial capacity cost is still the main obstacle for the wider preference of high efficient distributed energy system, reasonable incentive policy or direct subsidy is will play important role in achieving grid-supporting decentralized energy system. Grid operator must look beyond simply the technology and recognize what extent consumers (sustainable) can engage in demand side management. Estimated effects from demand side management will help the policy maker to develop relevant reasonable energy policy.

The main works and results can be summarized as follows:

In chapter one, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY, presents the developments of renewable technology, then states the opportunities and challenges for power supplier with increasing variable renewable integration, points the importance of building coordinate demand side management. Finally, illustrates the motivation and purpose of this research. In addition, the energy roadmap or relevant policy in Japan is introduced and related studies have been reviewed.

In chapter two, RESEARCH MOTIVATION AND METHODOLOGY. Firstly, the concept and approach for grid load management is described. Then previous research about impacts of renewable integration and role of storage system are described. Finally, the assessment approaches are illustrated, including residual load duration curve, screen curve method and evaluation for demand side management from bottom up perspective.

In chapter three, FEASIBILITY ANALYSIS OF VIRTUAL POWER PLANT. Feasibility of Virtual Power Plant (VPP) in Chongming Island is investigated, VPP is constructed based on resources from both supply and demand sides, strategies focus on expansion of renewable energy and upgrade of home appliances in demand side. Analysis results verify the effectiveness of VPP concept based on cooperation between supplier and customer. VPP shows relative short payback period (10 years) compared with conventional power plant, and achieved district annual power saving 273GWH/year. The energy market structure is changing due to the application of the VPPs, benefits power plant industry and incentives users' participation in demand sides.

In chapter four, ASSESSMENT OF RENEWABLE ENERGY INTEGRATION IN PLANT SIDE. The techno-economic viability of high variable renewable integration, grid flexibility and storage is investigated in this section. Firstly, electricity load and PV production in Kyushu Island are described. The impacts of increasing PV integration is illustrated in load duration curve. Storage dispatch is important for higher PV integration, PV-PHS dispatch scenarios are carried out based on simulation model with constraints, results indicate that pump hydro storage can play an effective role in promoting PV utilization via absorbing excess PV generation under grid flexibility limitation, PHS also effectively helps shave the peak load, enhancing grid flexibility. PHS effectively recovers the suppression and decreases the PV levelized cost of electricity especially under higher PV penetration, meanwhile shifts the curve of power supply merit order to right, decreasing the overall power generating cost. Simulation result shows PV-PHS can decrease the overall generation cost from 0.145$/kWh to 0.139$/kWh at 19% PV penetration level of public grid, pumping ability of PHS to peak load ratio is 0.15.

In chapter five, PERFORMANCE ANALYSIS OF DISTRIBUTED ENERGY SYSTEMS. Distributed energy planning covers technologies, the relevant market innovation and management. To get a better understanding of behavior of efficient power technologies based the applications in social demonstration projects in Kyushu. Then investigated the cost saving and environmental benefits of decentralized energy systems in residential sector under current energy market.

Combination of thermal storage and heat pump could be scheduled to lift the early morning valley period effectively. V2H brings more flexible option to the grid, aggregated EVs lifts valley grid load shaves the night period in absence of PV generation, potential cost saving and carbon emission reduction are achieved due to gasoline fuel consumption reduction. Generating ability of PV system shows great variation over months, the application of battery storage in residential PV system is investigated in detail. Aggregated PV-battery system can scheduled to increasing local self-consumption, meanwhile serve the grid for peak shaving. Relevant subsidies or further cost drop in battery is essential for the development of grid-supporting PV-battery system in residential sector. Cogeneration system (Fuel cell) operation highly depends on simultaneous thermal and power loads, power contribution shows limited contribution during summer or mid-season. The feasibility of CHP system is still highly dependent on access of direct subsidy due to high initial capital cost under current energy market, considering their potential flexible resource and carbon emission reduction chances. 500 thousand participation of proposed efficient energy systems cut 8.8% peak load at 20:00 pm in winter, 2500 MW distributed residential PV system (generally with 4-6 kWp capacity) can shoulder around 14% peak load during daytime in summer. Scheduled distributed energy resources could shave the peak grid load to reduce the output from peak-meeting plant, further decreases the overall generation cost.

In chapter six, MARKET INNOVATION AND SUGGESTIONS. From supplier perspective, the performance of dynamic price based demand response is investigated based on the social demonstration project. The behaviors of change in daily electricity consumption curves can be obviously observed in types of consumer sectors under the CPP (critical peak pricing) event, response performances of different customers are described. From demand side management perspective, the integration of electrical technologies in demand side can be optimized to provide flexibility to the public grid in a decentralized way. Incentive policy to grid-supporting power storage and residential CHP system is essential for their wider development.

In chapter seven, CONCLUSION AND OUTLOOK have been presented.

Further increasing intermittent renewable penetration poses challenges to the grid, storage, suppression and end-user participation can jointly stabilize the grid flexibility. Simulation results indicate that cost drop in renewable energy technologies will not increase the grid overall generation cost within reasonable RES penetration ratio. Optimal designed distributed energy systems can effectively participate in energy management at community or large scale. Increasing peak pricing shows a promising effect in releasing peak balancing pressure. Foundlings of research can provide meaningful insight for grid planner as they participate the growth of renewable energy resources and the strategies they should implement to meet flexibility requirement.

Outlook

Chapter 4 created load and generation profiles by averaging time series over a day of month, it can lead to deviation in the results of related simulation performance, underestimate the PV variability and PHS dispatch role due to smoothing effects in the curves of demand and PV production. Future work will focus on different time series aggregation methods in selecting typical days for energy supply modelling, and compare techno-economical performances of PV integration in different regions of Japan. From the technical perspective, the economic performance of storage dispatch is investigated based on pump hydro storage system, the feasibility of other flexible options such as power to gas and other battery storage techniques will be analyzed in future work

Chapter 5 verifies that aggregated high efficiency technologies can not only help the grid regulation but also reduce the social carbon emission. In terms of storage system for power regulation, especially under massive integration of intermittent renewable resources, next research will investigate the load shifting performance of combined on-site PV array with EV system for enhancing local PV self-consumption and analyze its potential economic benefit with the dropping feed-in tariff over coming decades.

Demand side management is mainly assessed in residential sector. Assessment of efficient decentralized energy system application in commercial or office sector will be carried out in further work. PV or cogeneration operation scenarios will be carried out with optimized management strategies, for example combine the prediction technique to increase local energy self-sufficiency, enhance renewable integration through sharing power generation within local or community grid.

Appendix: CODING OF ANALYSIS MODEL

The simulation models of thesis are built in MATLAB2014b environment.

1. PV integration modeling code in Chapter 4

```
% Daily cycle scenario in each month
grid=yload;%grid daily load in 12 month
grid=grid./max(grid);% normalized load
ypv=ypv./max(ypv);%normalized   PV generation
ratio=0.2;% PV production to load ratios vary as: 0.05,0.10,0.15,0.20
ypv=ratio/(sum(ypv)./sum(grid))*ypv;% produce PV production profile at specific ratio
ss=zeros(4,12);
ss1=zeros(24,12);
for j=1:12
index=j;%select specific month
%dispatch cycle
size=0.2*7;%power output to capacity ratio of pump hydro station is 7.0
state=0.15*size;%initial pump state
s=zeros(1,24);
dis=zeros(1,24);
% montly grid load, flexible demand and pv generation
grid=reshape(grid,24,[]);
PV=reshape(ypv,24,[]);
%select the specific month
PV=PV(:,index);
grid1=grid(:,index);
demand=grid(:,index)-0.35*max(grid1);
%charging period
for i=8:17
         s(i)=min(0.2*size,max(PV(i)-(demand(i)-0.3*max(demand)),0));%thermal flexibility limitation is set 0.3 to peak ratio
         state=state+(s(i)*0.85);%charging efficiency, 0.85
        if state>=0.95*size
        break
        s(i)=s(i)-(state-0.95*size);
        state=0.95*size;
        end
  end
```

```
%discharging period
if state>0.16*size
for i=18:24
        dis(i)=-min(max(demand(i)-0.3*max(demand),0),0.18*size);%thermal flexibility is limited within [0.2,0.7];
         state=state+(dis(i)/0.85);%discharge efficiency
        if state<=0.15*size
        break
        dis(i)=dis(i)+(0.2*size-state)
        state=0.15*size;
        end
end
end
%
if state>0.16*size
for i=1:7
        dis(i)=-min(max(demand(i)-0.3*max(demand),0),0.18*size);
        state=state+(dis(i)/0.85);
        if state<=0.15*size
        break
        dis(i)=dis(i)+(0.2*size-state);
        state=0.15*size;
        end
end
end
    s=s+dis;
for i=1:24
    m1(i)=max(0,min(demand(i)-0.3*max(demand),PV(i)));%directly consumed PV power,
    m(i)=max(0,min(demand(i)-0.3*max(demand),PV(i)-s(i)));%total power from PV and battery,
end
abs(sum(m))/sum(PV);%directly PV consumption ratio
abs(sum(m))/sum(demand);%PV self-sufficiency
for i=1:24
    buy(i)=demand(i)-abs(m(i));
    %buy(i)=demand(i)-abs(m1(i))+dis(i);
end
for i=1:24
```

```
        if -s(i)<0 %PV suppression
            sup(i)=PV(i)-m1(i)-s(i);
        else
            sup(i)=PV(i)-m1(i);
        end
end
%fugure
figure
box on
hold on
plot(m1)%directly consumption
plot(-s)%battery
buy=buy+0.35*max(grid1);
plot(buy)%import from grid to meet load, constant output
plot(-sup)% PV suppression
plot(grid1')%grid load
legend('Direct integration','PHS flow','Import from grid','Supression','Grid load')
set(gca, 'XTick', [1 4 8 12 16 20 24]);
set(gca,'XTickLabel',{'0:00','4:00','8:00','12:00','16:00','20:00','24:00'})
set(gca,'FontName','Times New Roman','FontSize',12)
xlim([1 24])
xlabel('Time')
ylabel('Electricity')
abs(sum(m))/sum(PV); % PV self-consumption
abs(sum(m))/sum(grid1);% PV penetration in grid
data=[demand,m1',-s',buy',sup'];
ss1(:,j)=buy';
ss(:,j)=[abs(sum(m))/sum(PV);state;abs(sum(m))/sum(grid1);abs(sum(sup))]; % results for month
end
```

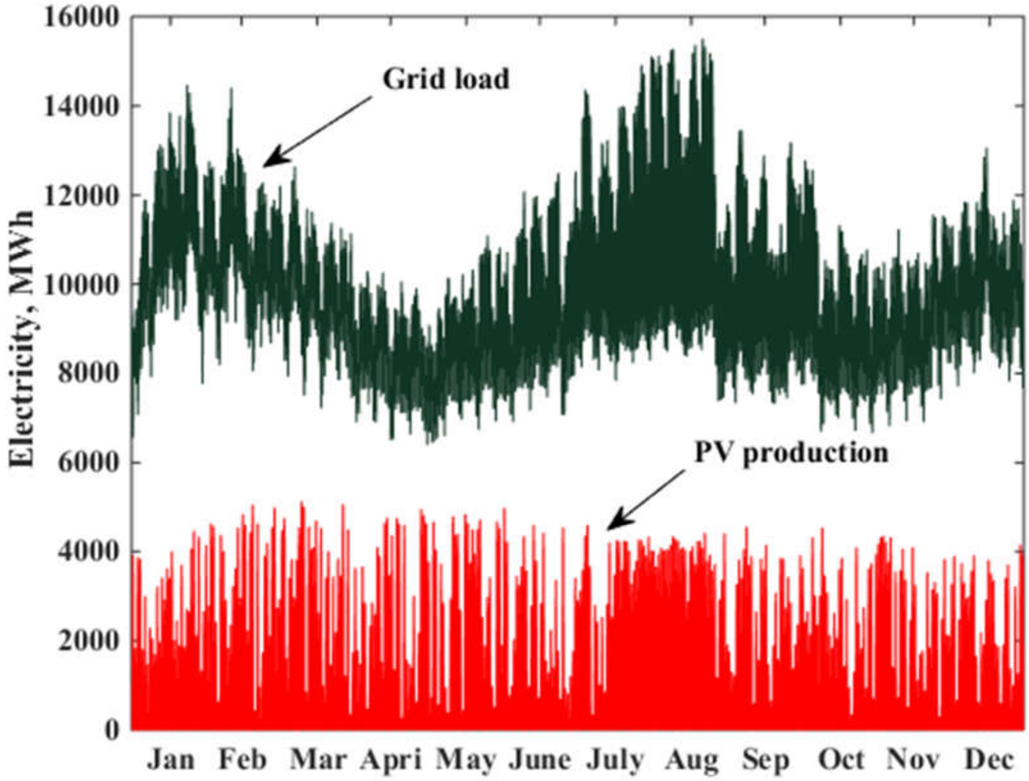
2. PV-battery modeling code in Chapter 6

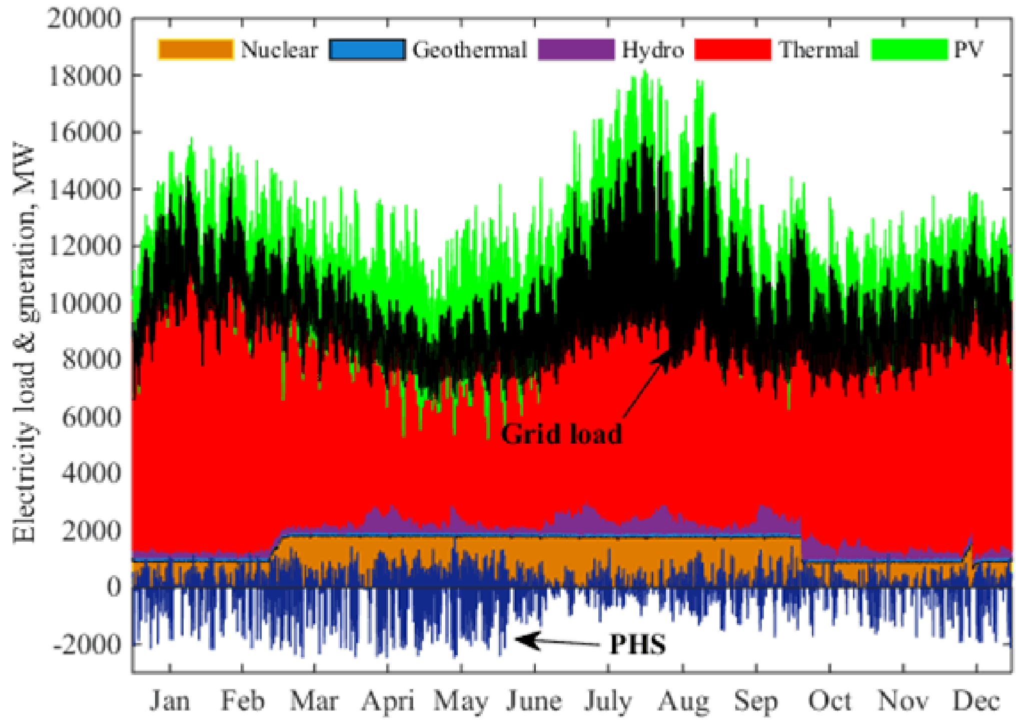
```
load w % load weather data
r=w(:,1); % solar irradiation
t=w(:,2);% temperature
cap=30; % determine nominal capacity of PV system
PV=cap*0.15*r.*(1-0.005*(t-25)); % simulate PV generation
PV=smooth(PV,'moving');
load residentialdemandaverage
demand=smooth(demand,'moving');
size=3;% battery is 3kWh
state=0.2*size; %initial state of battery
s=zeros(1,48);
dis=zeros(1,48);
demand=reshape(demand,48,[]);
PV=reshape(PV,48,[]);
demand=demand(:,8);% select August load
PV=PV(:,8);% select August PV production
% public grid information
load grid2
grid3=smooth(grid2,'moving');
grid3=grid3./max(grid3);
g=reshape(grid3,48,[]);
grid=g(:,8);
%charging
for i=1:48
        s(i)=min(0.2*size,max(0,PV(i)-demand(i)));
        state=state+(s(i)*0.95)*0.5;%half hour interval
        if state>=0.95*size
            s(i)=s(i)+(0.95*size-state)/0.5;
          break
        end
end

%discharging
for i=32:48
        %dis(i)=-min(0.4*demand(i),0.15*size);
        dis(i)=-min(demand(i),0.15*size);
        state=state+(dis(i)/0.9)*0.5;
```

```
        if state<=0.2*size
            dis(i)=dis(i)-(state-0.2*size)/0.5;
            break
        end
end
for i=1:16
        %dis(i)=-min(0.4*demand(i),0.15*size);
        dis(i)=-min(demand(i),0.15*size);
        state=state+(dis(i)/0.9)*0.5;
        if state<=0.2*size
            dis(i)=dis(i)-(state-0.2*size)/0.5;
            break
        end
end
    s=s+dis;
for i=1:48
    m1(i)=min(demand(i),PV(i));%directly consumed PV power
    m(i)=min(demand(i),PV(i)-s(i));%total power from PV and battery
end
abs(sum(m))/sum(PV);%directly PV consumption ratio
abs(sum(m))/sum(demand);%PV self-sufficiency
for i=1:48
    buy(i)=demand(i)-abs(m(i));
    %buy(i)=demand(i)-abs(m1(i))+dis(i);
end
for i=1:48
    if -s(i)<0
        sold(i)=PV(i)-m1(i)-s(i);
    else
        sold(i)=PV(i)-m1(i);
    end
end
figure
box on
hold on
plot(demand)%residential demand
plot(PV)%PV generation
set(gca, 'XTick', [1 8 16 24 32 40 48]);
```

```
set(gca,'XTickLabel',{'0:00','4:00','8:00','12:00','16:00','20:00','24:00'})
set(gca,'FontName','Times New Roman','FontSize',12)
figure
hold on
plot(m1)%directly consumption
plot(-s)%battery
plot(buy)%import from grid
plot(-sold)%sold to grid
legend('Direct consumed','Battery flow','Buy from grid','Sell to grid')
set(gca, 'XTick', [1 8 16 24 32 40 48]);
set(gca,'XTickLabel',{'0:00','4:00','8:00','12:00','16:00','20:00','24:00'})
set(gca,'FontName','Times New Roman','FontSize',12)
xlim([1 48])
xlabel('Time')
ylabel('Electricity')
abs(sum(m))/sum(PV)% PV self-consumption
abs(sum(m))/sum(demand)% PV self-sufficiency
abs(sum(PV))/2 %PV daily production in kWh
data=[demand,m1',-s',buy',sold'];
PV1=m1'-dis'+sold'; %equivalent PV load with storage dispatch
```

Data source: Kyushu grid load and PV production profile in 2017





Reference: Kyuden Power Company. http://www.kyuden.co.jp/wheeling_disclosure.html